Network Coding in Wireless Systems: Impact of Wireless Links

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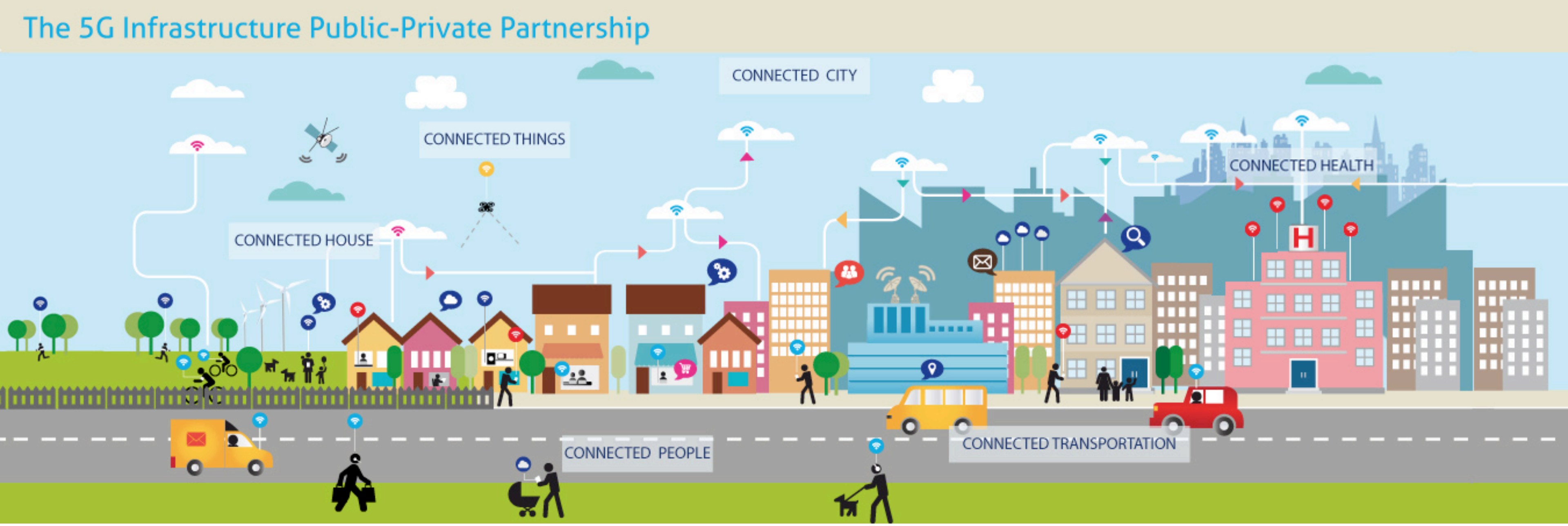
Outline

- Motivation
- Main Concepts
  - Network Coding
  - Cooperative Networking
  - Cooperative Network Coding
- Wireless Channels
- Wireless Network Coded Systems
  - System Model
  - Simulation Results
  - OFDMA extension
- Testbed Deployment & Test Results
- Future Work & Conclusions

Motivation

5G Infrastructure Public-Private Partnership (http://5g-ppp.eu/)



Current Status of Wireless Networks

- Increasing number of terminals
- Increasing data rate demands
- Constant (or decreasing) radio resources

→

More efficient network architectures are required

An Option: Network Coding (1/3)

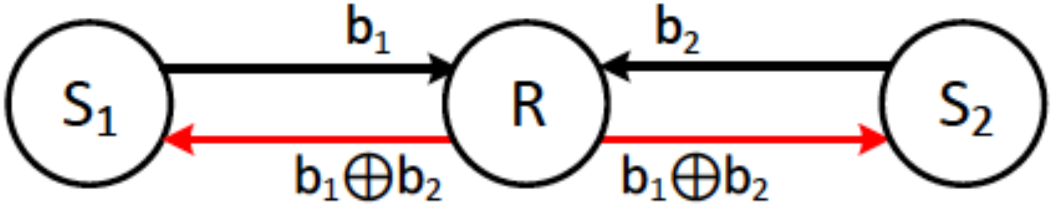
- Conventional communication systems:
  - Network nodes function independently
    - Routing, error control coding and data storage have been designed in accordance with this independency principle
- Data flow rates form source nodes to destination nodes in a network can be increased by transmitting combinations of data [1]
- Stemming from the early works of in the form of multi-level diversity [2]

[1] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung, "Network information flow," IEEE Trans. Inf. Theory, vol. 46, no. 4, pp. 1204–1216, July 2000.

[2]R. Yeung, "Multilevel diversity coding with distortion," Information Theory, IEEE Transactions on, vol. 41, no. 2, pp. 412–422, Mar 1995.

An Option: Network Coding (2/3)

- Example: Two way relay channel



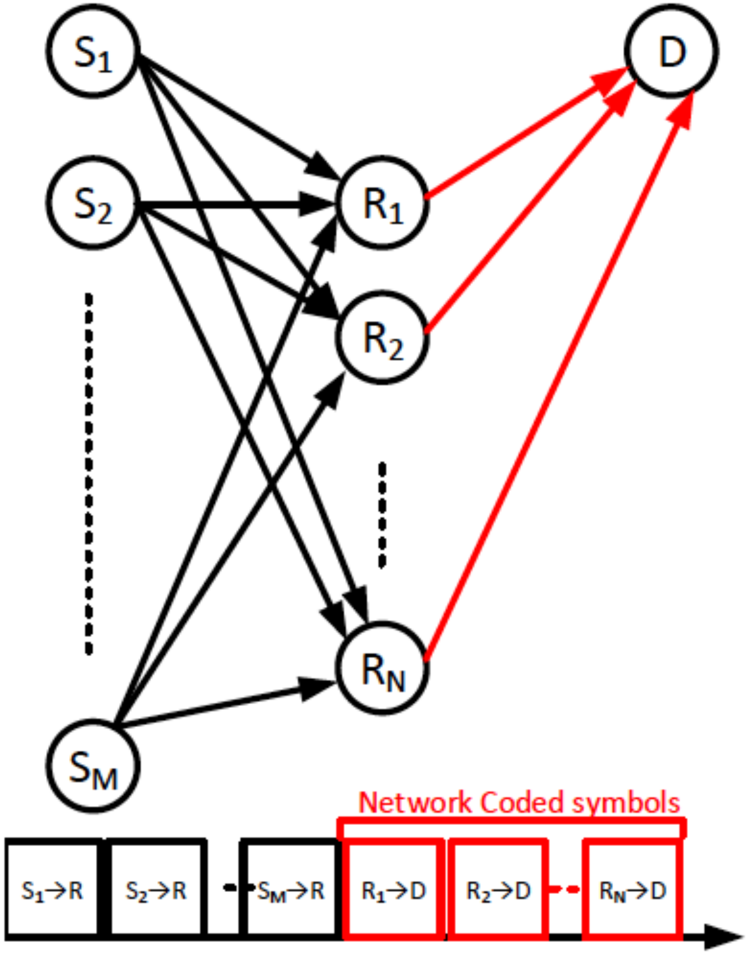
- Routing solution:
  - Total Transmission Time: 4T
- Network coding solution
  - Total Transmission Time: 3T
- Physical layer network coding
  - Total Transmission Time: 2T

An Option: Network Coding (2/3)

- Generalized set-up:
  1. BROADCAST PHASE

     Source nodes transmit information symbols in N orthogonal resource block (time slots or frequency channels) during the multiple access phase (solid black lines) to relay nodes.
  2. RELAYING PHASE

     N relay nodes perform network coding on the M estimated symbols and transmit in N resource blocks in the to destination



The majority of the literature on network coding targets wired networks
(or application layer deployments)

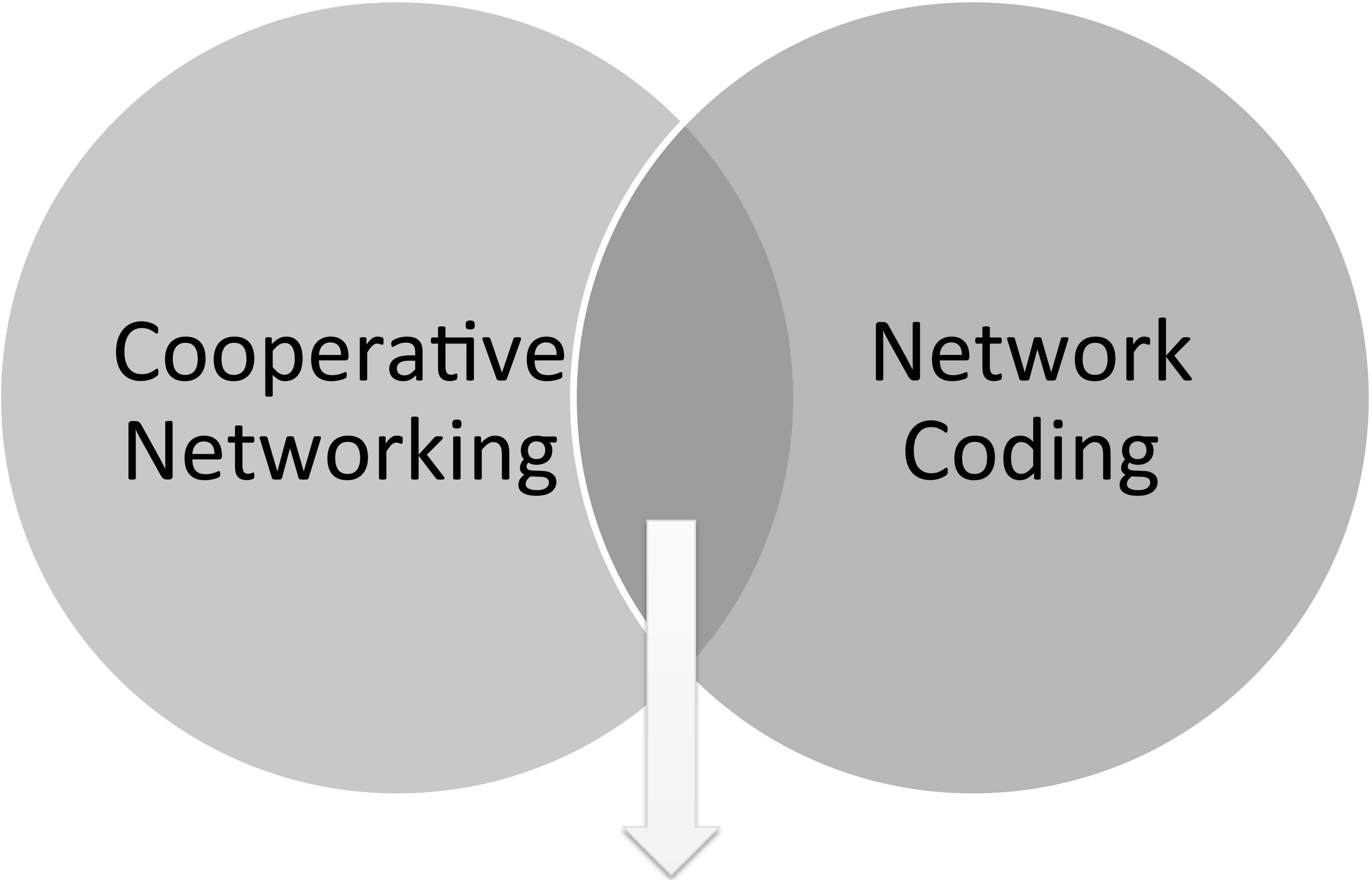
Assumption: no erroneous transmissions

What about error propagation?

Main Idea

Wired Network Coding ≠ Wireless Network Coding

1. Fading channels
2. Direct source-destination links
   - Cooperative Diversity
   - Detector Design



Cooperative Networking

Network Coding

Network Coded Cooperation

Cooperative Networking (1/2)

Goal: To significantly improve the error performance of the system.

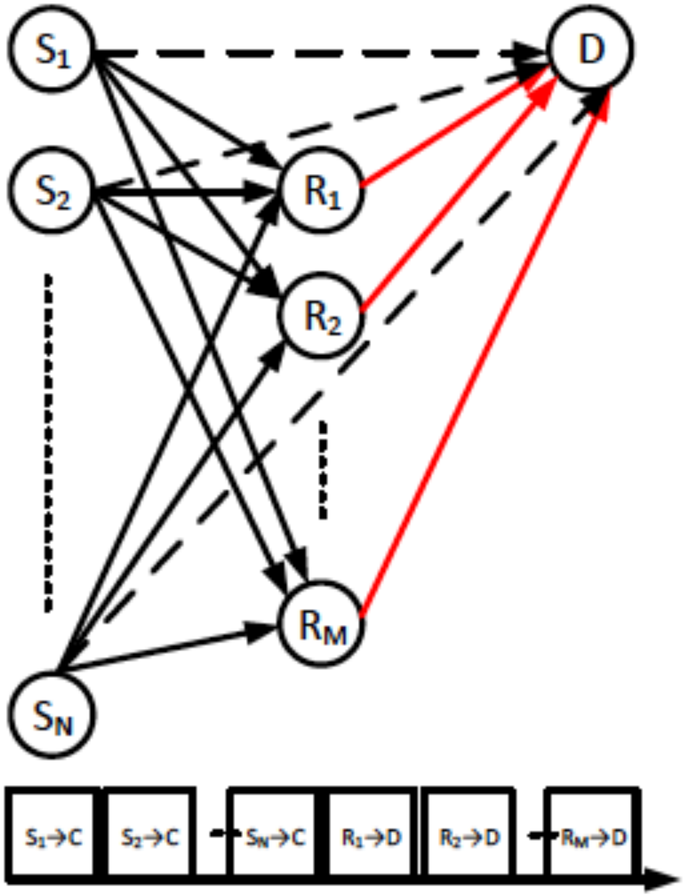
1. Broadcast Phase:

   As source node transmits, the overhearing relay nodes can repeat the received signals

2. Relaying Phase

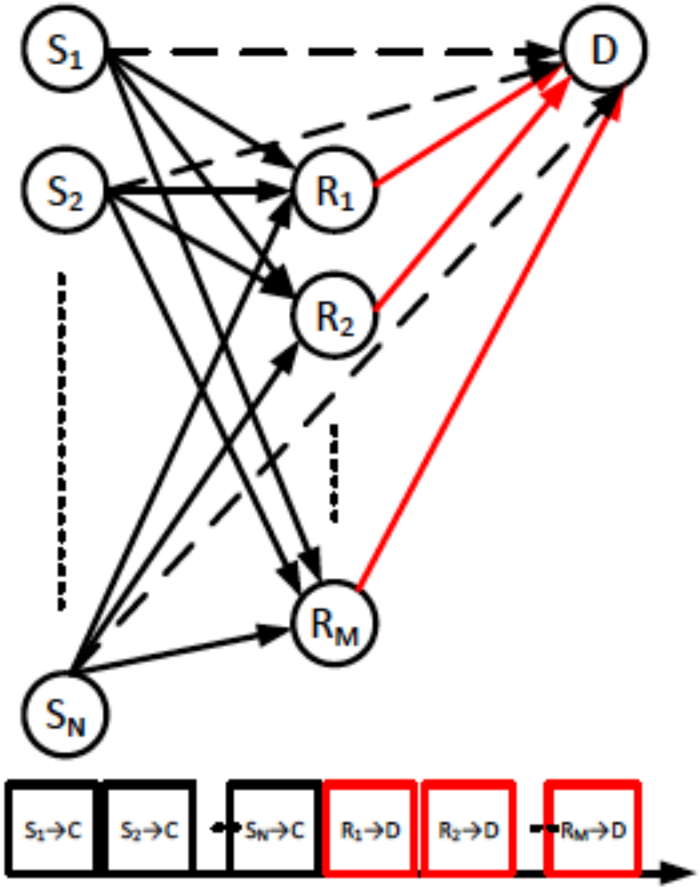
   The destination can combine all received copies of the information signal

Cooperative Networking (2/2)



- Cooperative networking techniques can help us exploit **spatial diversity**
  - hence combat the performance degrading effects of the wireless fading channels.
- Makes use of the broadcast nature of the wireless channel,

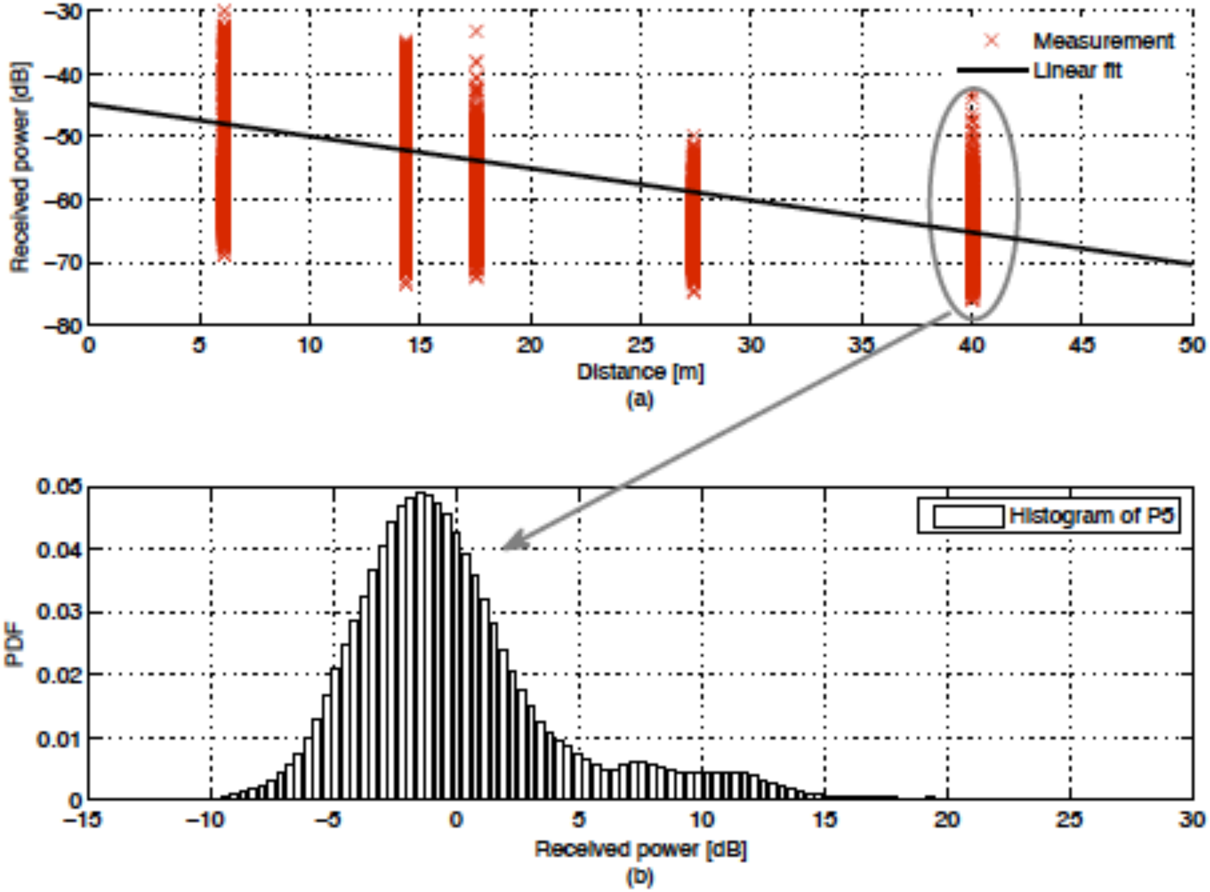
Network Coded Cooperation



- Combining network coding and cooperative networking
- Can exploit the intrinsic characteristics of wireless networks to improve
  - Throughput
  - Robustness.
- Based on the preliminary works of Chen, Kishore and Li in [3].

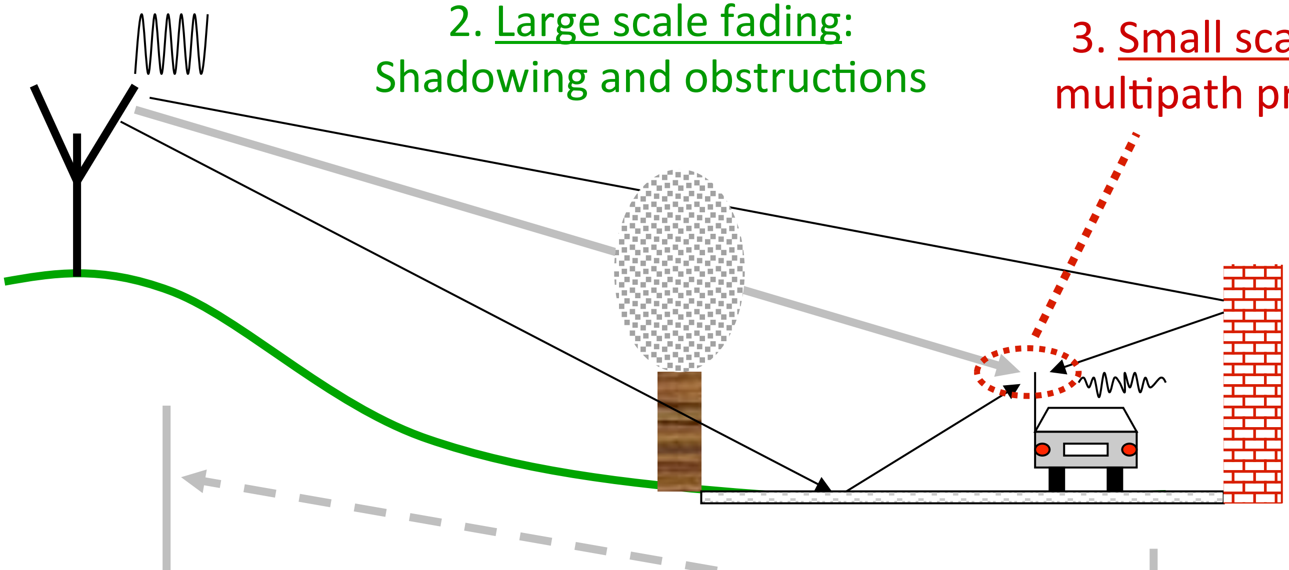
[3] Y. Chen, S. Kishore, and J. Li, "Wireless diversity through network coding," WCNC 2006

What’s Fading?



Measurement Based Evidence

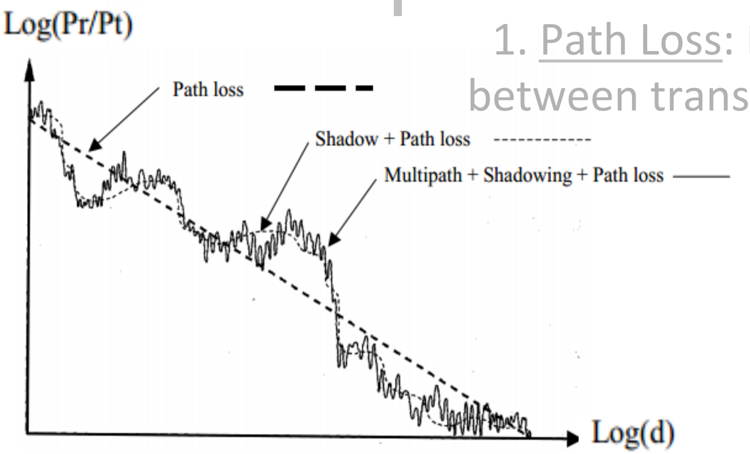
Wireless Channels



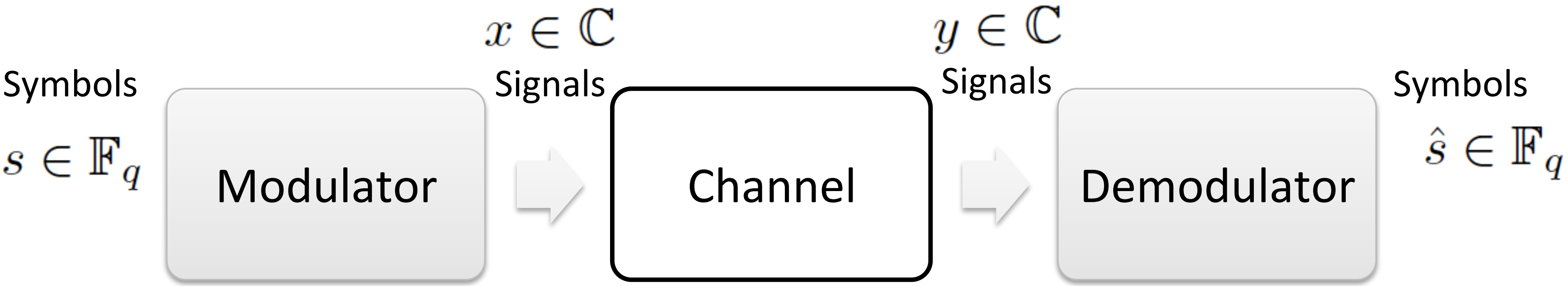
2. Large scale fading:
Shadowing and obstructions

3. Small scale fading:
multipath propagation

1. Path Loss: Based on distance between transmitter and receiver



Wireless Channel Models (1/2)



Symbols $s \in \mathbb{F}_q$

Modulator

$x \in \mathbb{C}$ Signals

Channel

$y \in \mathbb{C}$ Signals

Demodulator

Symbols $\hat{s} \in \mathbb{F}_q$

Performance Metrics:

Outage probability

Symbol error rate

$$y = hx + n$$

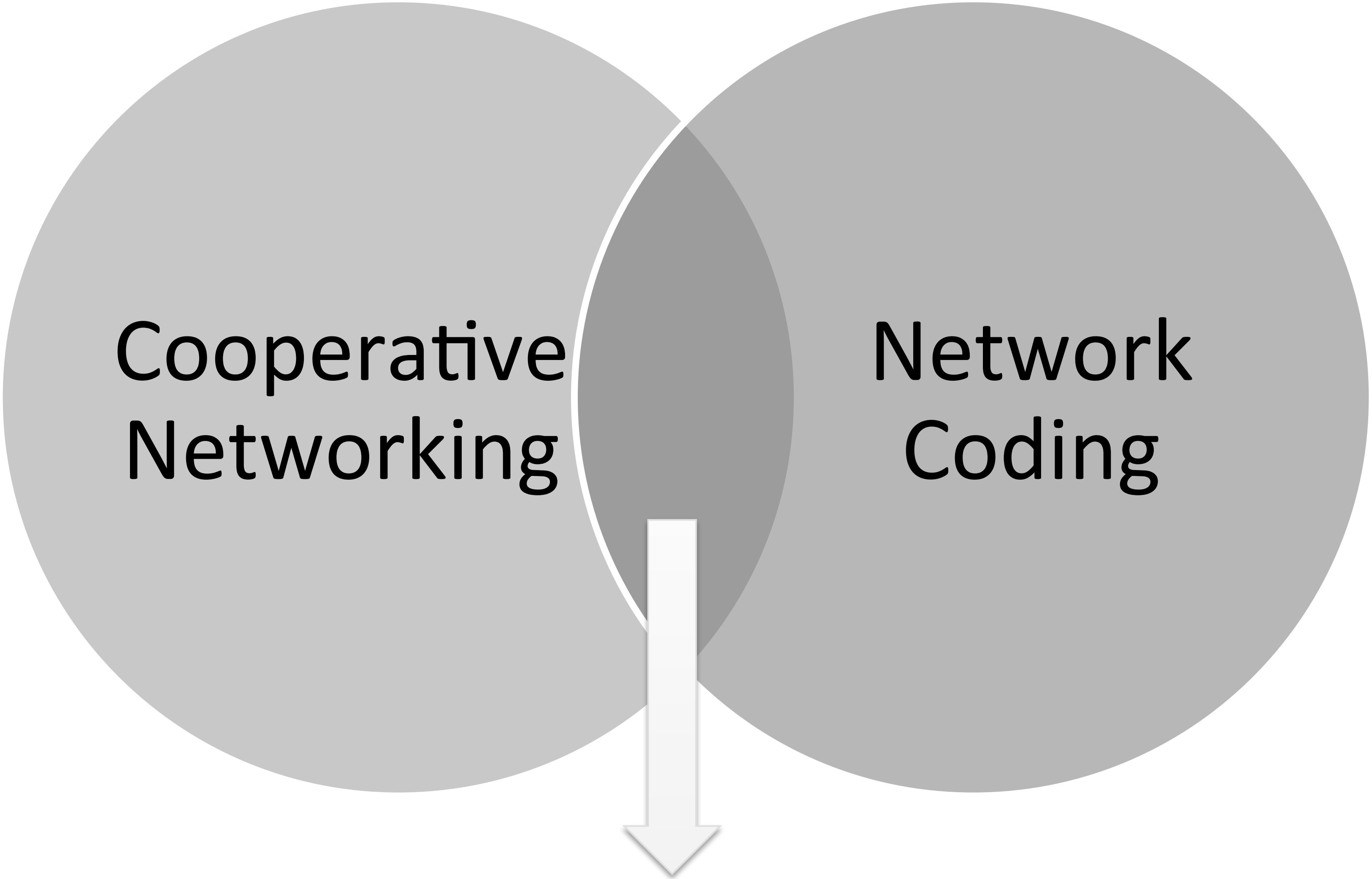
Fading Channel

Additive white Gaussian noise (AWGN)

$$n \in \mathbb{C} \qquad n \sim \mathcal{N}(0, \sigma^2)$$

$$h \in \mathbb{C}$$

+ Wireless Channels



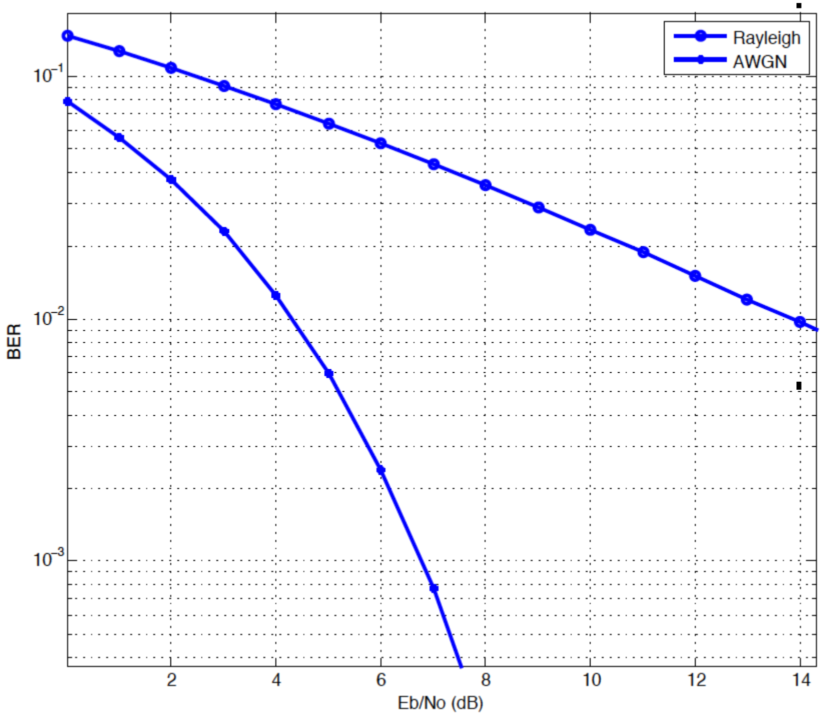
Cooperative Networking

Network Coding

Network Coded Cooperation

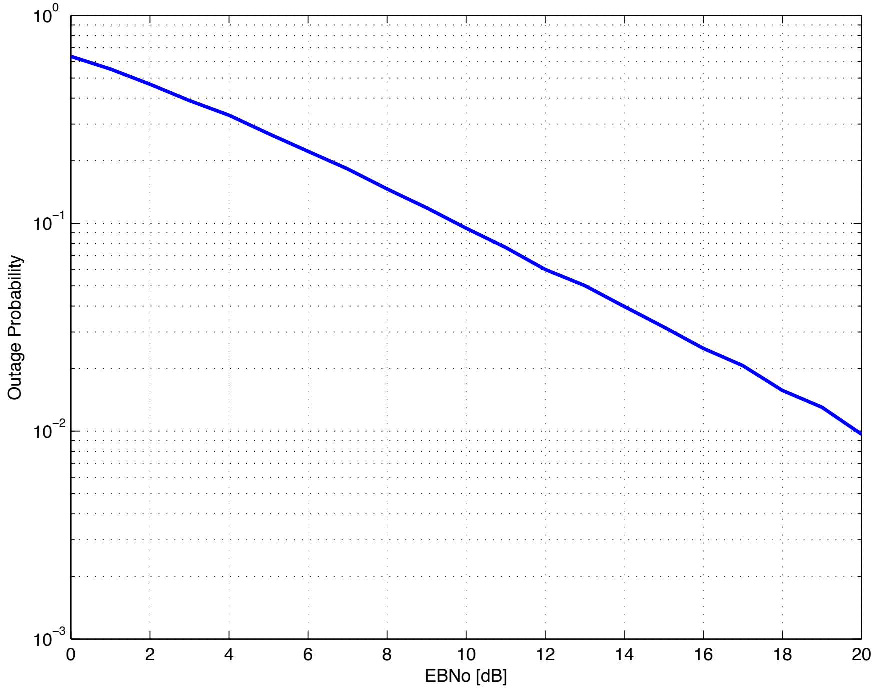
Impact #1: Error/Outage Rates

$$\boxed{Pr(s \neq \hat{s})}$$

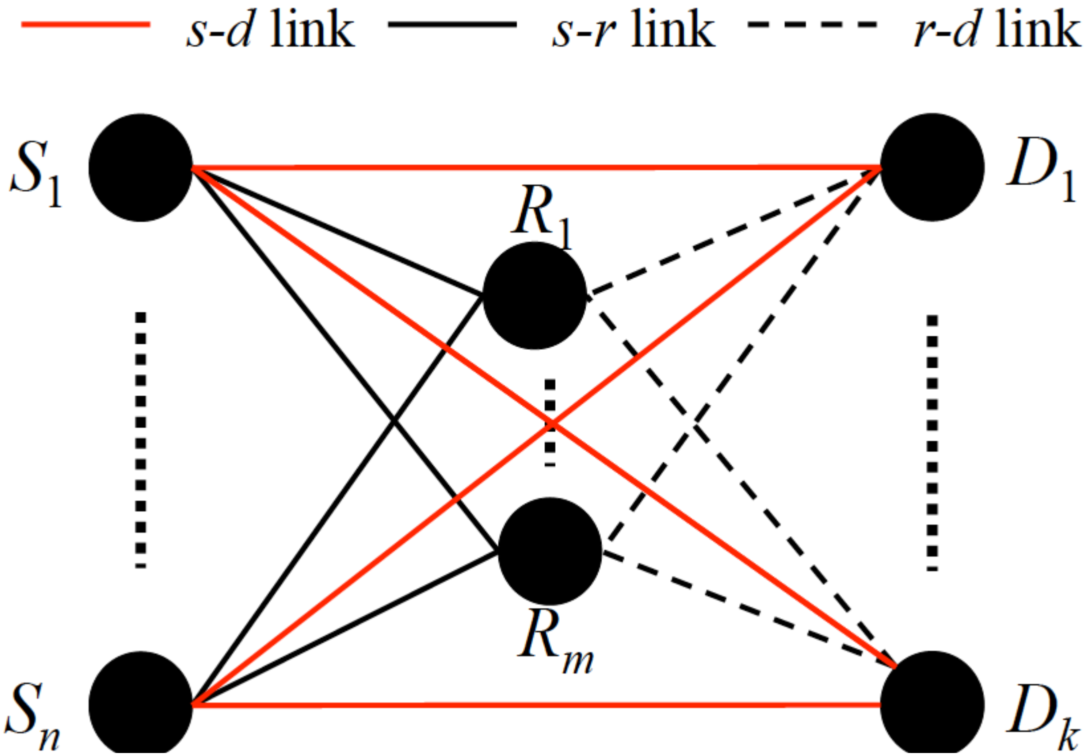


$$\boxed{\overline{\mathrm{P}}_{\mathrm{e}} = \int_0^{\infty} \mathrm{P}_{\mathrm{e}}(x) p_{\gamma_{\mathrm{s}}}(x) dx}$$

$$\boxed{Pr(\frac{|h|^2 E_b}{\sigma^2} < \gamma)}$$



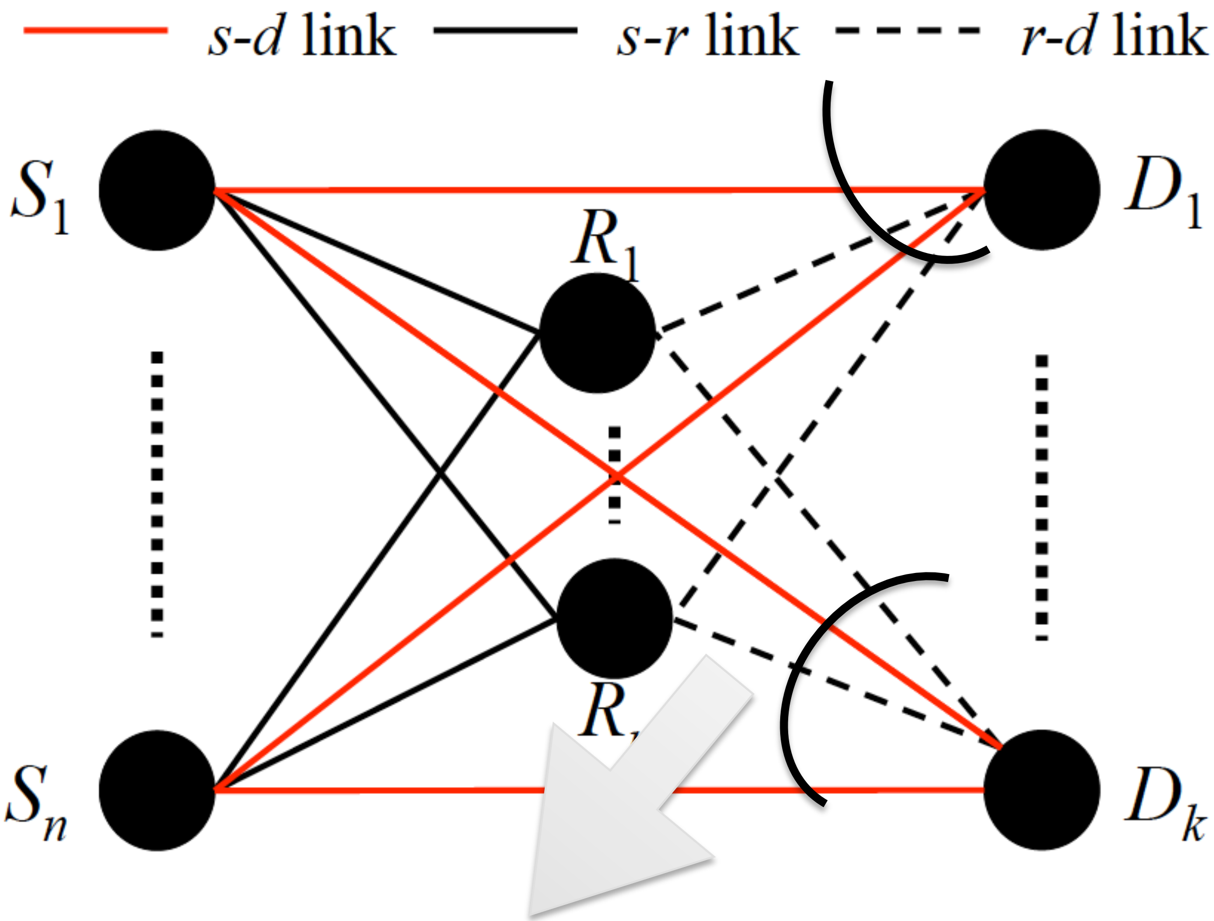
Impact #2: Source-Destination Links



Global Encoding Matrix

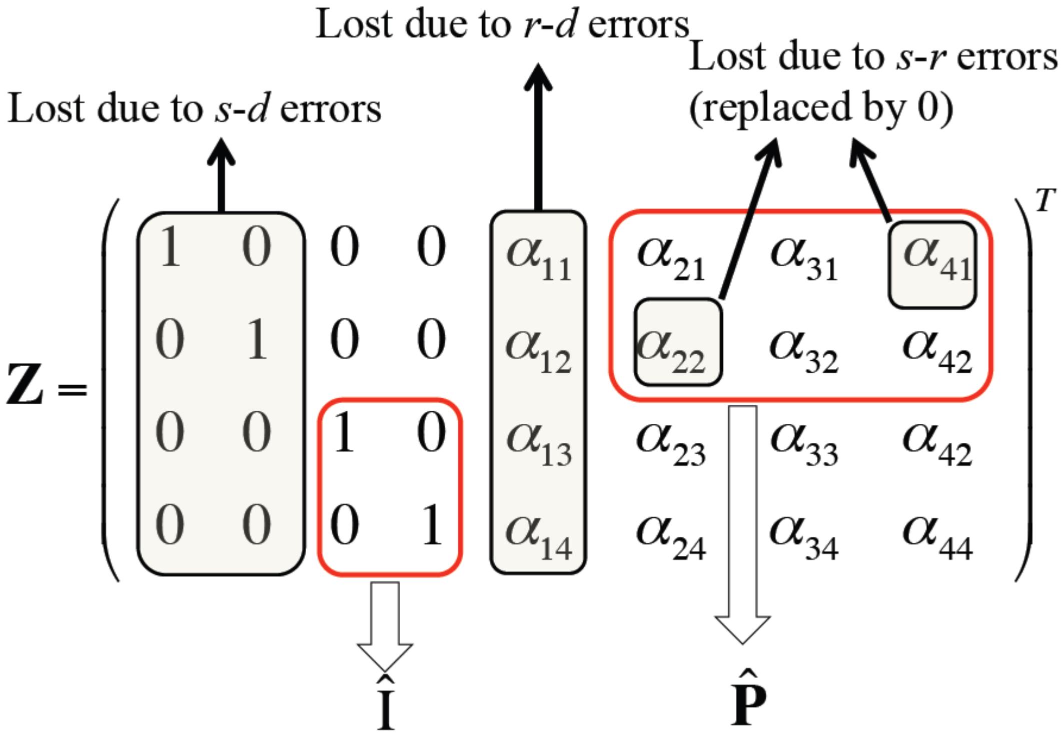
$$\mathbf{Z} = \left(\begin{array}{cccc|ccc} 1 & 0 & \cdots & 0 & \alpha_{11} & \cdots & \alpha_{m1} \\ 0 & 1 & \cdots & 0 & \alpha_{12} & \cdots & \alpha_{m2} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \alpha_{1n} & \cdots & \alpha_{mn} \end{array}\right)^T \qquad \mathbf{Z} \in \mathbb{F}_q^{(n+m)\times n}$$

Combined Impacts:



Each link has a nonzero error/erasure probability

Example: 4 source nodes, 4 relay nodes, broadcast transmission (1/3)



Lost due to *s-d* errors

Lost due to *r-d* errors

Lost due to *s-r* errors (replaced by 0)

$$\mathbf{Z} = \begin{pmatrix} 1 & 0 & 0 & 0 & \alpha_{11} & \alpha_{21} & \alpha_{31} & \alpha_{41} \\ 0 & 1 & 0 & 0 & \alpha_{12} & \alpha_{22} & \alpha_{32} & \alpha_{42} \\ 0 & 0 & 1 & 0 & \alpha_{13} & \alpha_{23} & \alpha_{33} & \alpha_{42} \\ 0 & 0 & 0 & 1 & \alpha_{14} & \alpha_{24} & \alpha_{34} & \alpha_{44} \end{pmatrix}^T$$

$\hat{\mathbf{I}}$

$\hat{\mathbf{P}}$

$$P(S \rightarrow D) = \phi_{SD}$$

$$P(S \rightarrow R) = \phi_{SR}$$

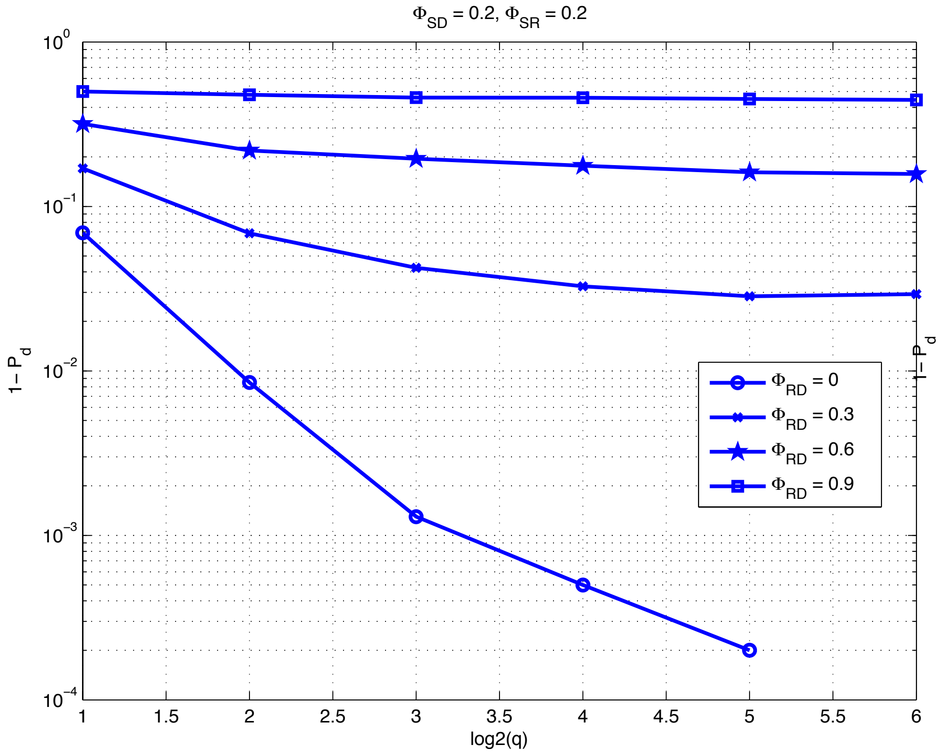
$$P(R \rightarrow D) = \phi_{RD}$$

Example: 4 source nodes, 4 relay nodes, broadcast transmission (2/3)

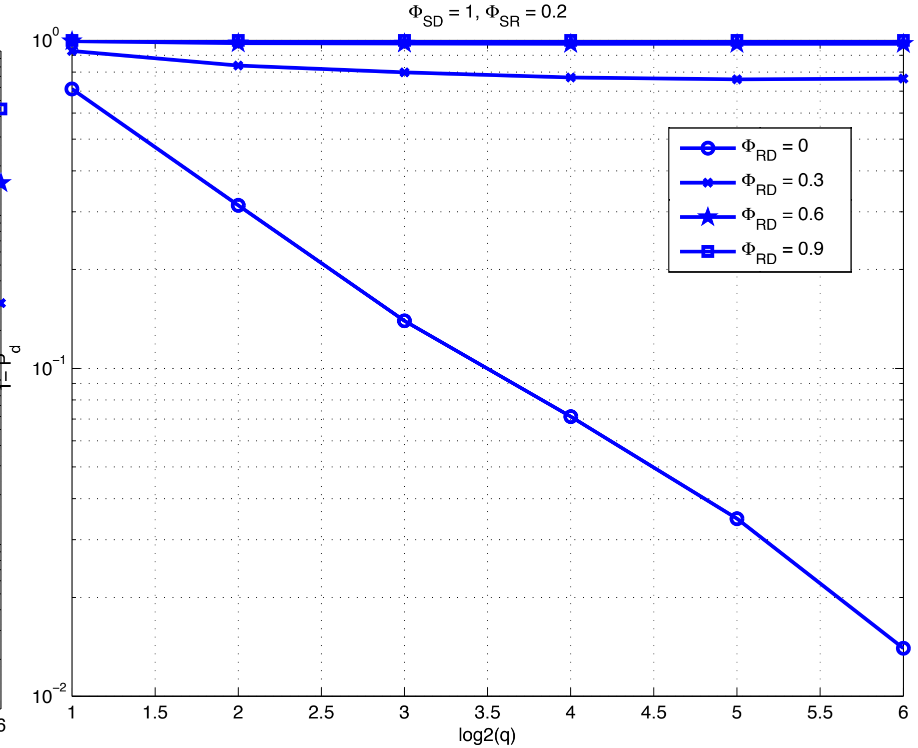
- Cooperative Random Network Coding
- Relay applies random linear network code [4]
  - Each relay randomly selects a coefficient from a finite field with q elements for the data received from a source.
- Erasure model is assumed
- Rank based detector is employed

[4] T. Ho, M. Medard, R. Koetter, D. Karger, M. Effros, J. Shi, and B. Leong, “A random linear network coding approach to multicast,” IEEE Trans. Inf. Theory, vol. 52, no. 10, pp. 4413-4430, Oct. 2006.

Example: 4 source nodes, 4 relay nodes, broadcast transmission (3/3)



Non-ideal S-D link

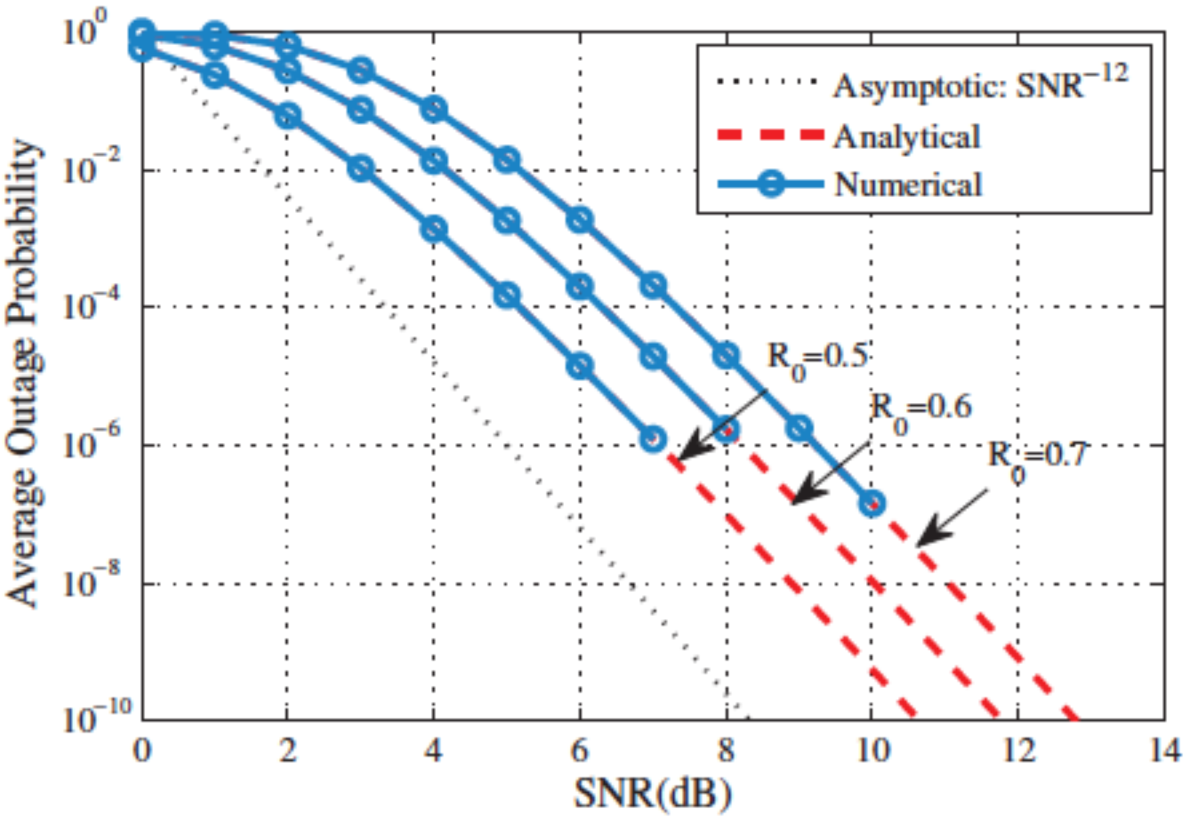


No S-D link

no direct transmission link between source & destination nodes

Extension to OFDMA (1/2)

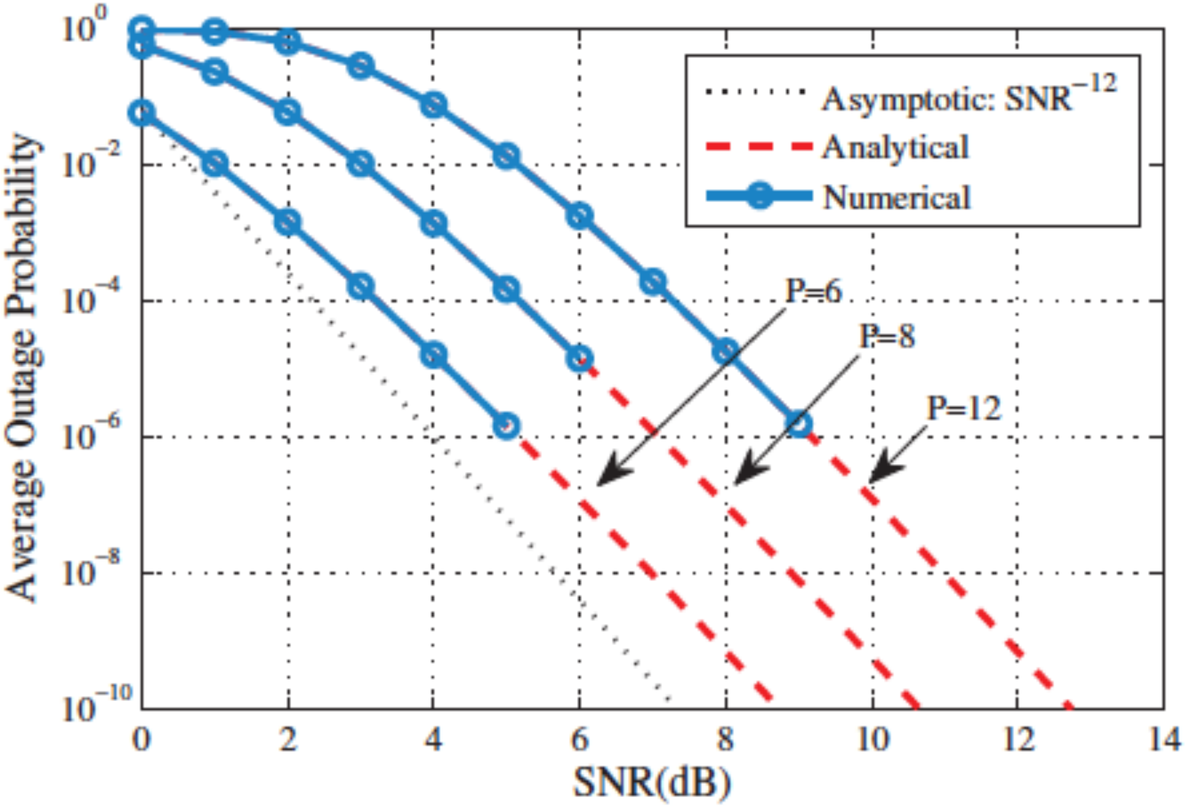
- The number of coherence bandwidths: 4
- The number of subcarriers: 128
- The number of source nodes: 8
- The number of relays: 2



[5] A. Heidarpour , G. Karabulut Kurt, M. Uysal, 'Diversity-Multiplexing Tradeoff for Network Coded Cooperative OFDMA Systems' accepted for publication, ICC 2015

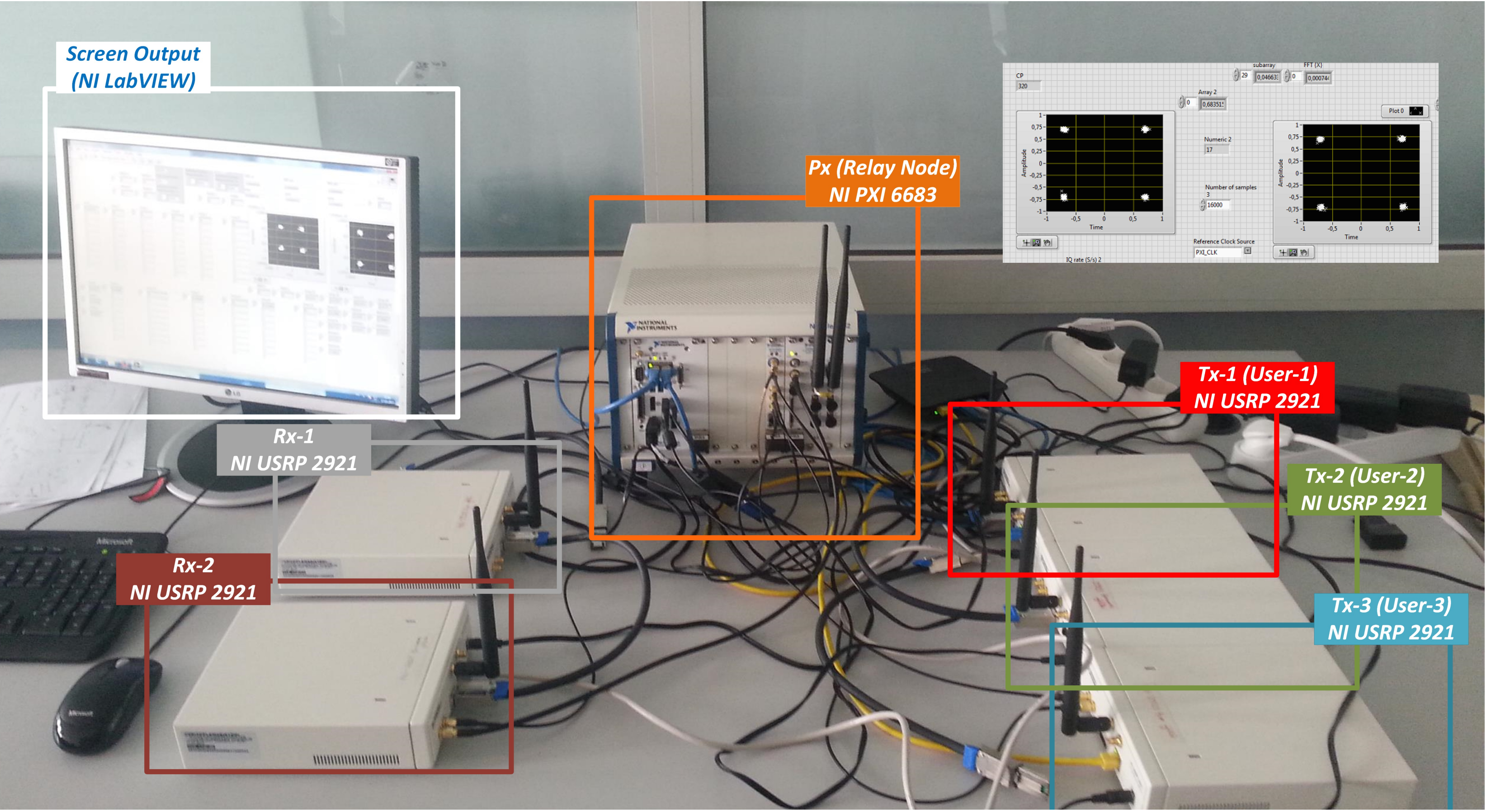
Extension to OFDMA (2/2)

- The number of coherence bandwidths: 4
- The number of subcarriers: 128
- Transmission rate 0.5
- The number of relays: 2



[5] A. Heidarpour , G. Karabulut Kurt, M. Uysal, 'Diversity-Multiplexing Tradeoff for Network Coded Cooperative OFDMA Systems' accepted for publication, ICC 2015

Testbed Deployment (1/2)



CP 320

subarray 29 0,04663

FFT (X) 0 0,000744

Array 2 0 0,683515

Numeric 2 17

Number of samples 3 16000

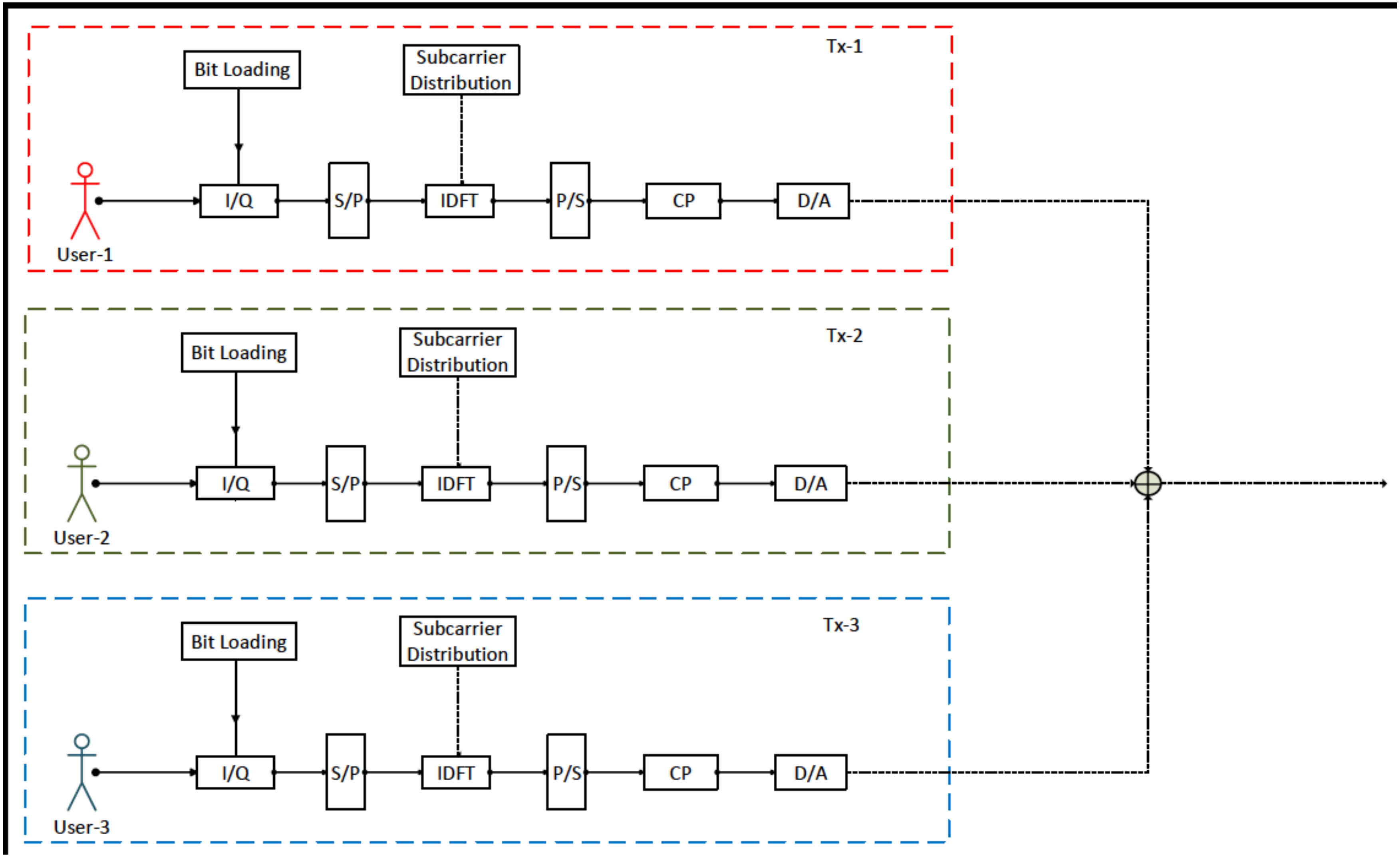
Reference Clock Source PXI_CLK

IQ rate (S/s) 2

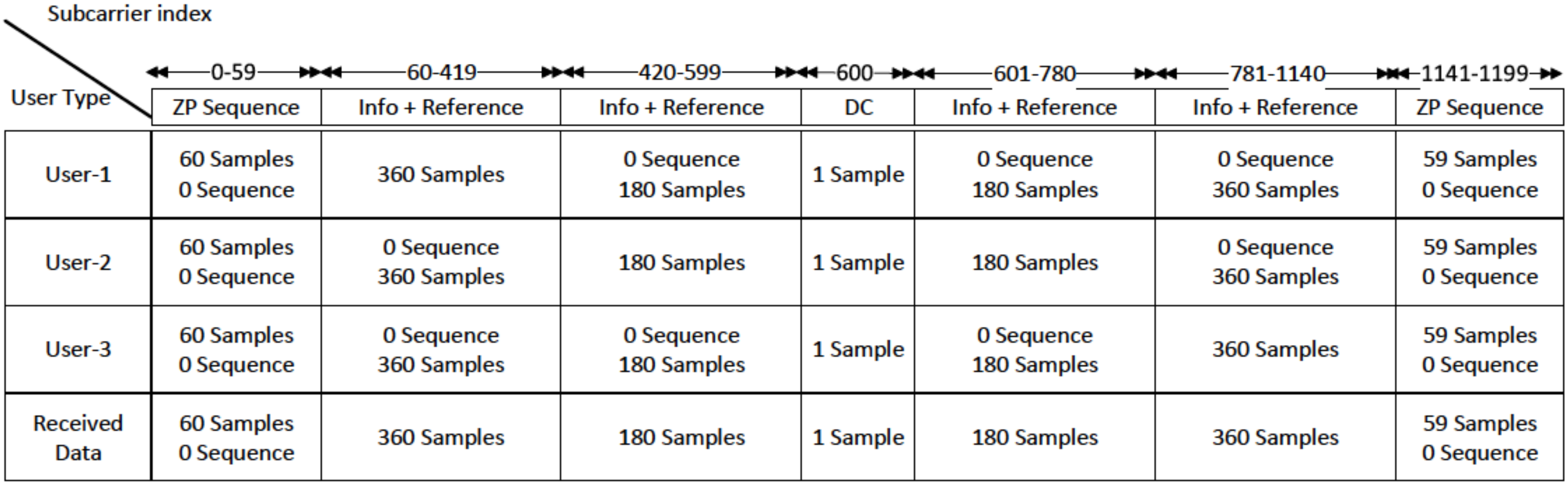
OFDMA based Transmitters

Network Coding at Relay Node

Broadcast Phase

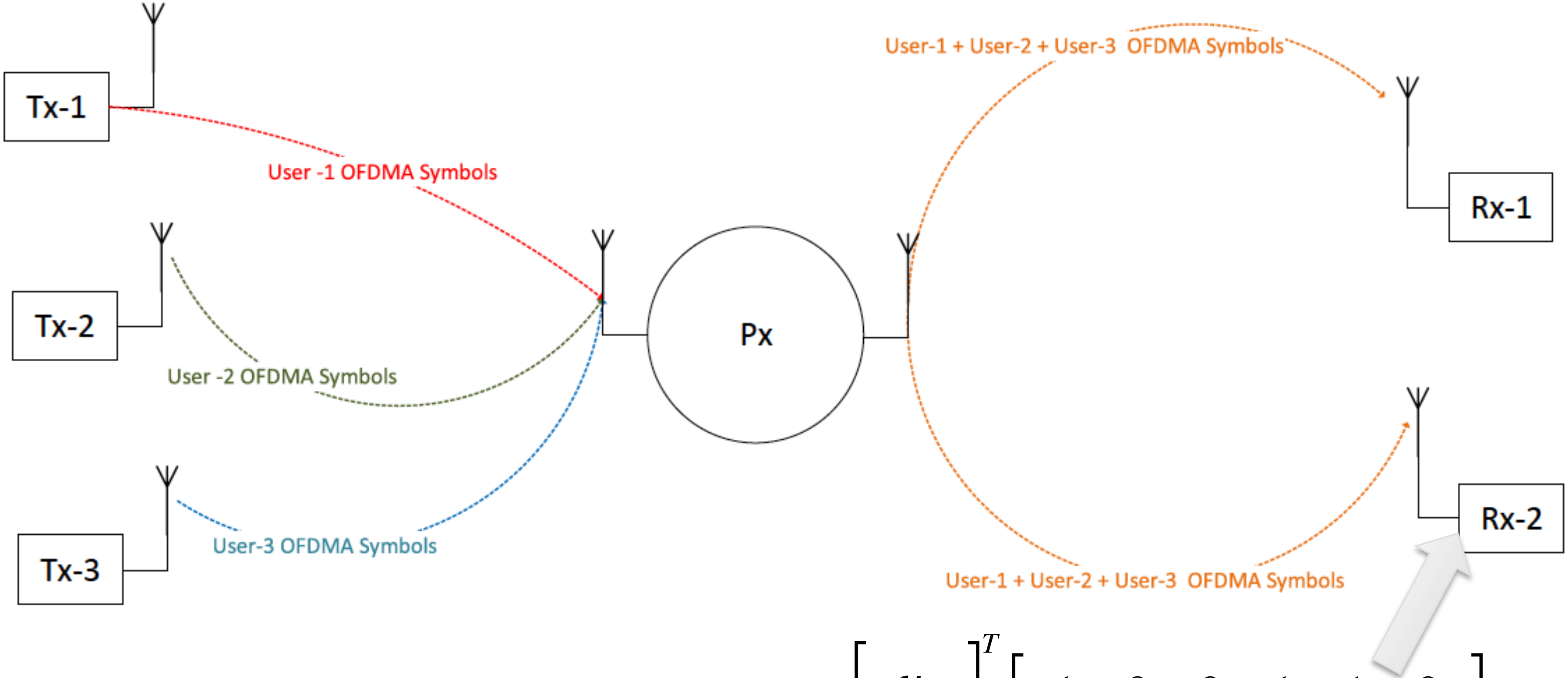


Frame Structure



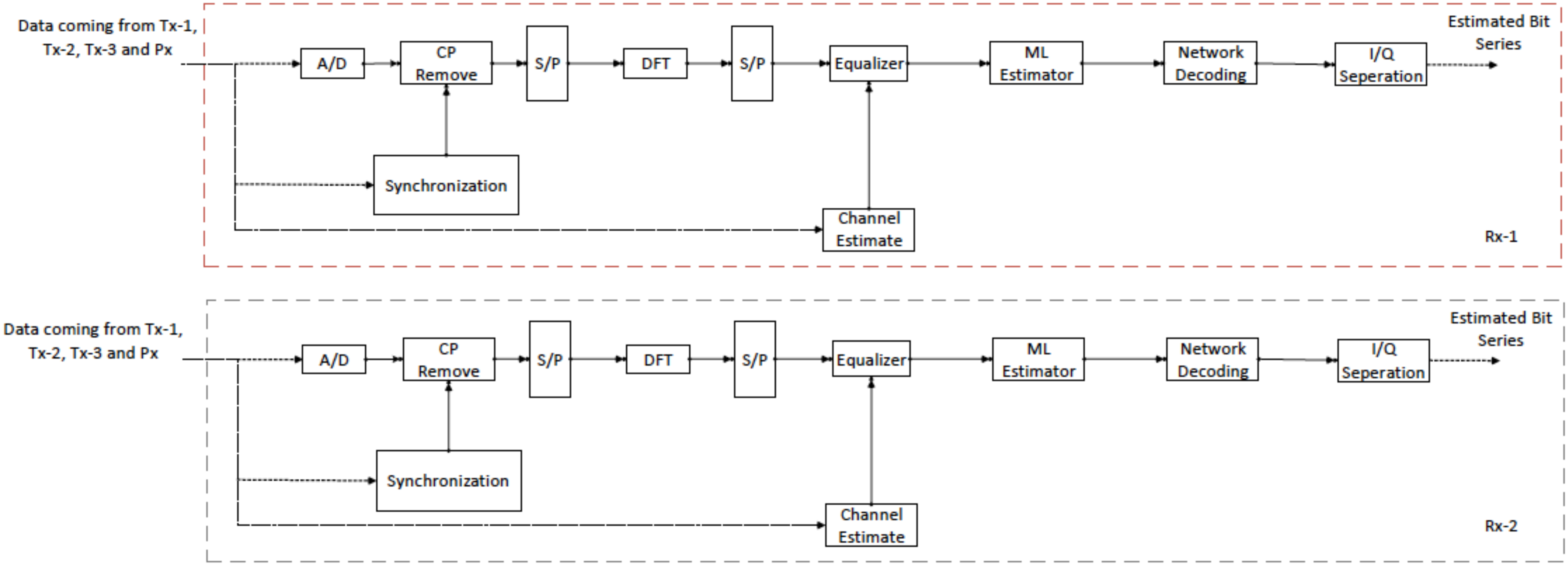
Subcarrier index	0-59	60-419	420-599	600	601-780	781-1140	1141-1199
User Type	ZP Sequence	Info + Reference	Info + Reference	DC	Info + Reference	Info + Reference	ZP Sequence
User-1	60 Samples 0 Sequence	360 Samples	0 Sequence 180 Samples	1 Sample	0 Sequence 180 Samples	0 Sequence 360 Samples	59 Samples 0 Sequence
User-2	60 Samples 0 Sequence	0 Sequence 360 Samples	180 Samples	1 Sample	180 Samples	0 Sequence 360 Samples	59 Samples 0 Sequence
User-3	60 Samples 0 Sequence	0 Sequence 360 Samples	0 Sequence 180 Samples	1 Sample	0 Sequence 180 Samples	360 Samples	59 Samples 0 Sequence
Received Data	60 Samples 0 Sequence	360 Samples	180 Samples	1 Sample	180 Samples	360 Samples	59 Samples 0 Sequence

Relaying Phase & NCC



$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}^T \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}$$

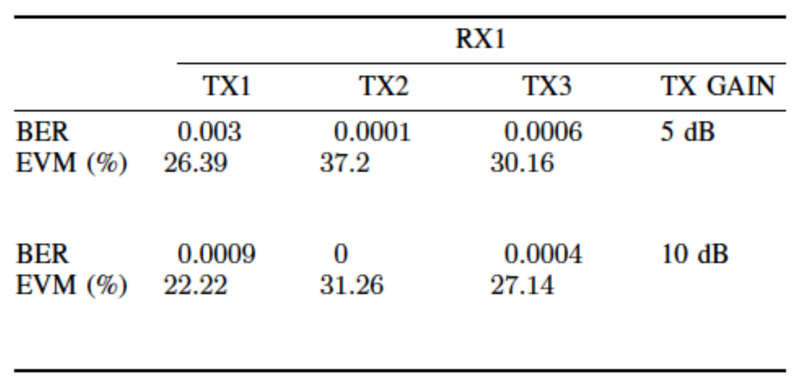
Receivers at Destination Nodes



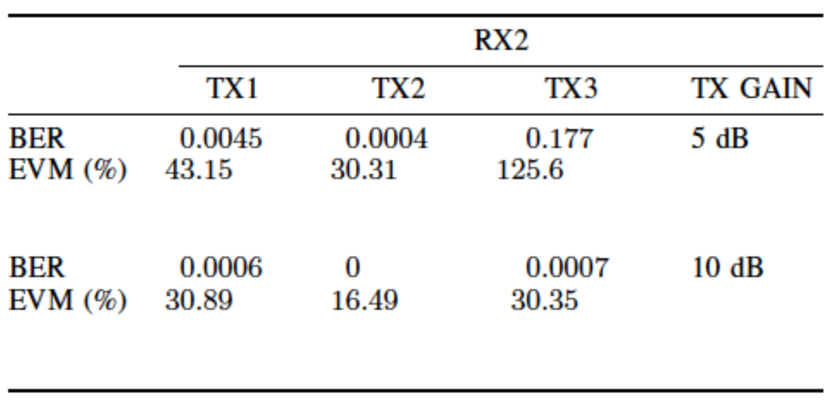
Another commonly used simplifying assumption:
The availability of the ideal channel state information (CSI)
Measured by using a limited number of pilot channels CSI may not always be ideal (every 8th subcarrier in this test set-up).

Test Results

Direct Link

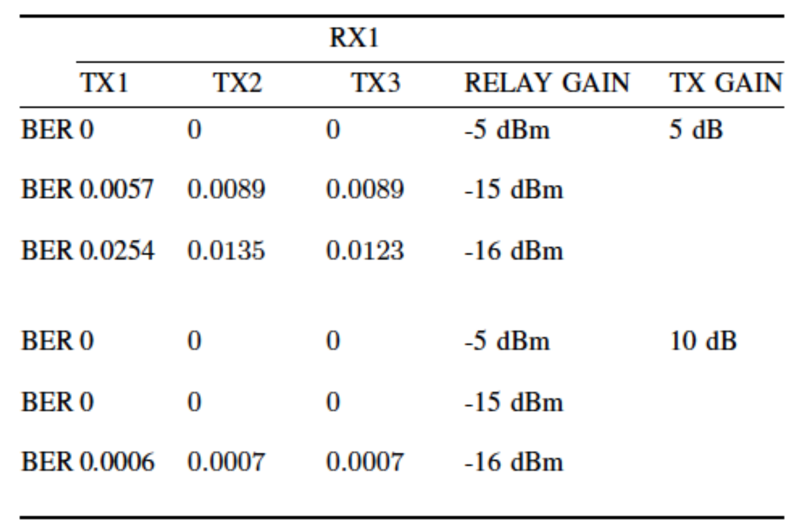


	RX1			
	TX1	TX2	TX3	TX GAIN
BER	0.003	0.0001	0.0006	5 dB
EVM (%)	26.39	37.2	30.16	
BER	0.0009	0	0.0004	10 dB
EVM (%)	22.22	31.26	27.14	

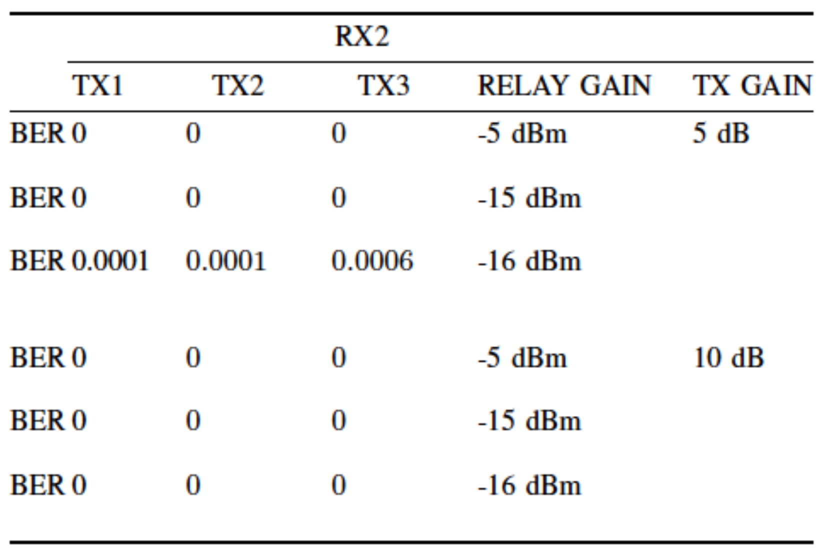


	RX2			
	TX1	TX2	TX3	TX GAIN
BER	0.0045	0.0004	0.177	5 dB
EVM (%)	43.15	30.31	125.6	
BER	0.0006	0	0.0007	10 dB
EVM (%)	30.89	16.49	30.35	

NCC



	RX1				
	TX1	TX2	TX3	RELAY GAIN	TX GAIN
BER	0	0	0	-5 dBm	5 dB
BER	0.0057	0.0089	0.0089	-15 dBm	
BER	0.0254	0.0135	0.0123	-16 dBm	
BER	0	0	0	-5 dBm	10 dB
BER	0	0	0	-15 dBm	
BER	0.0006	0.0007	0.0007	-16 dBm	



	RX2				
	TX1	TX2	TX3	RELAY GAIN	TX GAIN
BER	0	0	0	-5 dBm	5 dB
BER	0	0	0	-15 dBm	
BER	0.0001	0.0001	0.0006	-16 dBm	
BER	0	0	0	-5 dBm	10 dB
BER	0	0	0	-15 dBm	
BER	0	0	0	-16 dBm	

Future Work

- Impact of the Selected Network Code & Constellation Shape
- Further Physical Layer Related Problems:
  - Resource allocation (power/frequency/time)
  - Channel estimation
  - Synchronization
  - Multirate modulations

Conclusions

- For practical applicability the impact of the wireless channel needs to be considered ➔Cooperative network coding systems
  - Non-zero error/erasure rates
  - Direct source destination links
  - Nonideal estimation characteristics

Thank you for your attention

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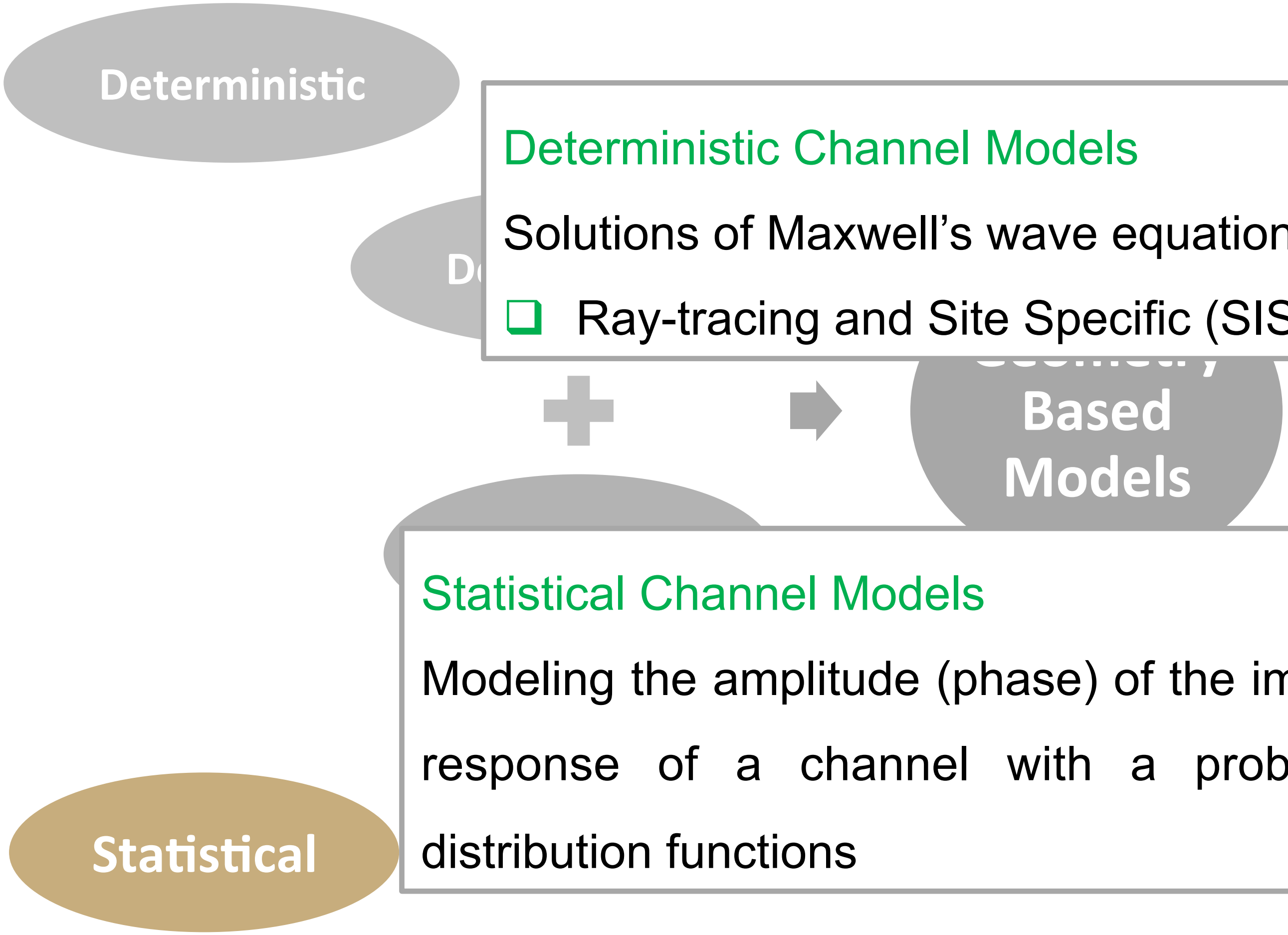
This work is supported by TUBITAK under Grant 113E294 & COST IC1104

Wireless Channel Models (2/2)



Deterministic Channel Models

Solutions of Maxwell's wave equations

- ❑ Ray-tracing and Site Specific (SISP)

Statistical Channel Models

Modeling the amplitude (phase) of the impulse response of a channel with a probability distribution functions

Log-distance path loss

Received signal strength decreases logarithmically with increasing distance (verified by both theoretical and empirical results.)

Average Path Loss:

$$\overline{PL}(d) \propto \left({}^{d}/_{d_0}\right)^{n}$$

$$\overline{PL}_{[dB]} = \overline{PL}(d_0) + 10n\log\left({}^{d}/_{d_0}\right)$$

Environment	Path loss exponent
Free space	2
Urban Environment	2.7 – 3.5
Shadowed Urban Environment	3 -5
Indoor line of sight (LoS)	1.6 – 1.8
Obstructed Indoor	4 -6

Empirical Models:

- ☐ Okumura: Urban macrocell 1-100km, 0.15-1.5GHz, BS antenna height 30-100m
- ☐ Hata: ~Simplified Okumura Model
- ☐ COST 231: Hata model extended to 2GHz

Lognormal Shadowing

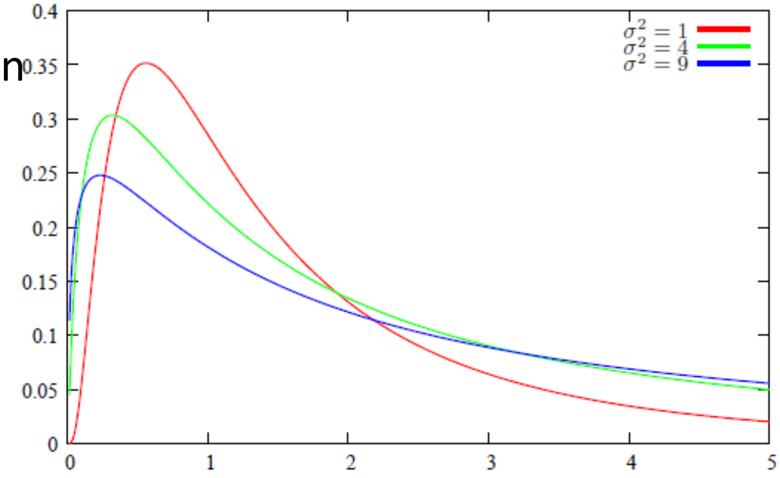
(Large-scale fading)

$$\overline{PL}_{[dB]} = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10n\log\left({}^{d}/_{d_0}\right) + X_\sigma$$

Lognormal distribution

Normal distribution

$$Y_\sigma = \prod_{i=1}^{N} Y_i \quad \xrightarrow{X_\sigma = \log(Y_\sigma)} \quad X_\sigma = \sum_{i=1}^{N} X_i$$



Central limit theorem

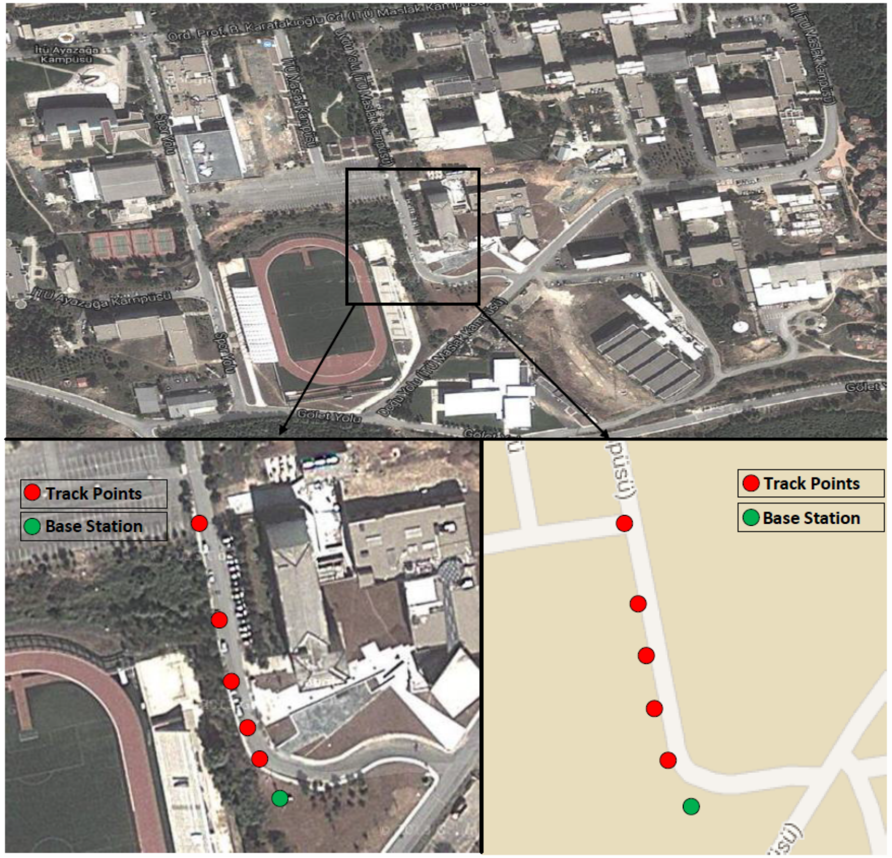
$$f_Y(y) = \frac{1}{y\sqrt{2\pi\sigma}} \exp\left(-\frac{(\log y - \mu)^2}{2\sigma^2}\right) \qquad \sigma^2 \in [4,12]$$

Lognormal Mixture Model

(Large Scale Fading)

Weighted mixture of lognormal shadowing

$$Y \sim f_Y(y) = \sum_{k=1}^{K} \omega_k \mathcal{LN}(\mu_k, \sigma_k^2)$$

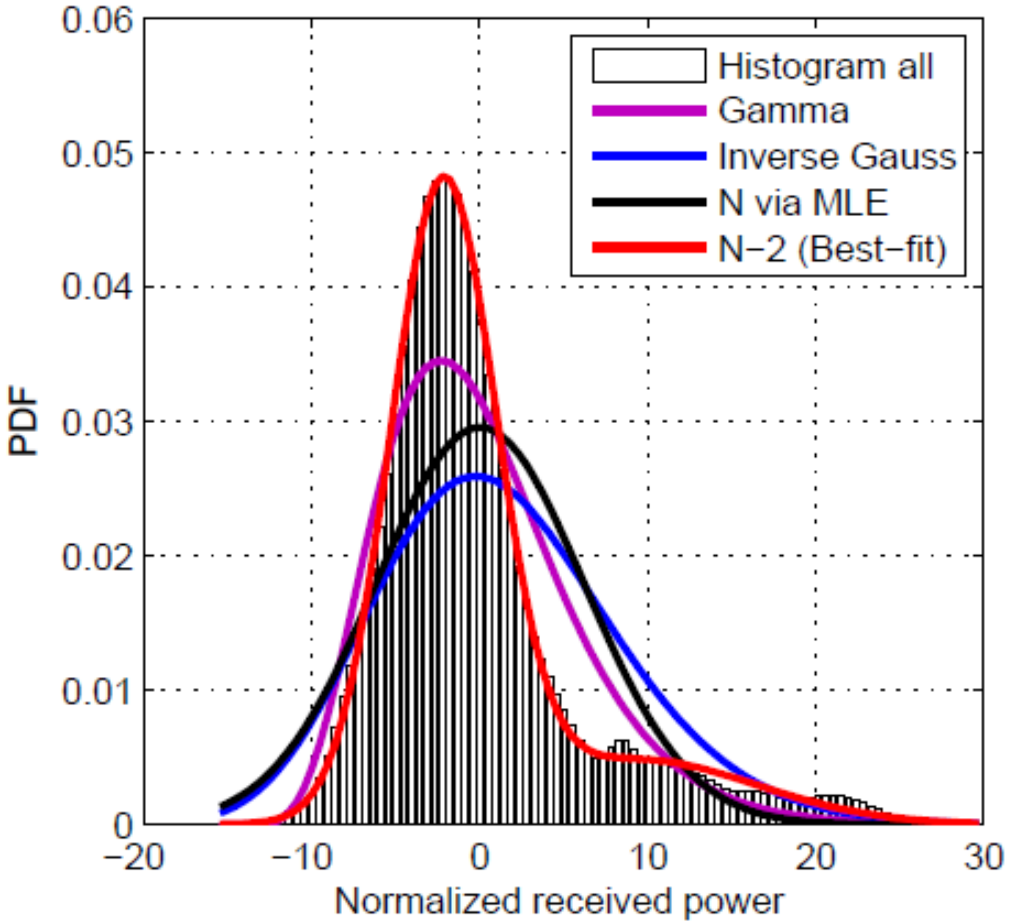


GENERAL MEASUREMENT PROPERTIES	
Scenario	Urban macrocell
Location	Istanbul Technical University Maslak Campus
Measurement setup	1 Base Station, 5 tracks, 10041 data points
Track distances from base station	5m, 10m, 15m, 24m, 40m
CHANNEL SOUNDER PROPERTIES	
Make/Model	Anritsu MS2711E
Center frequency	940.51MHz
Sweep time	17ms

[4] S. Buyukcorak, M. Vural, and G. Karabulut Kurt, “Lognormal Mixture Shadowing,” IEEE Transactions on Vehicular Technology, accepted for Publication

Lognormal Mixture Model

(Large Scale Fading & Composite Fading)



Small-scale Fading Models (1)

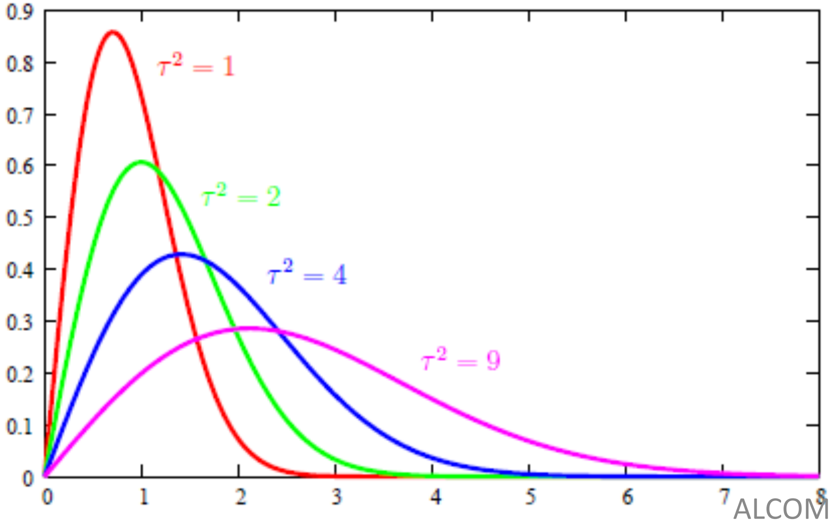
☐ Rayleigh Distribution (NLoS)

$$r(t) = e^{j2\pi ft}\{X(t) + jY(t)\}$$

$$X(t), Y(t) \sim \mathcal{N}(0, \sigma^2/2)$$

- Amplitude $R = \sqrt{X(t)^2 + Y(t)^2}$

$$f_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$$



☐ Ricean Distribution (LoS)

$$X(t) \sim \mathcal{N}(\upsilon_1, \sigma^2)$$

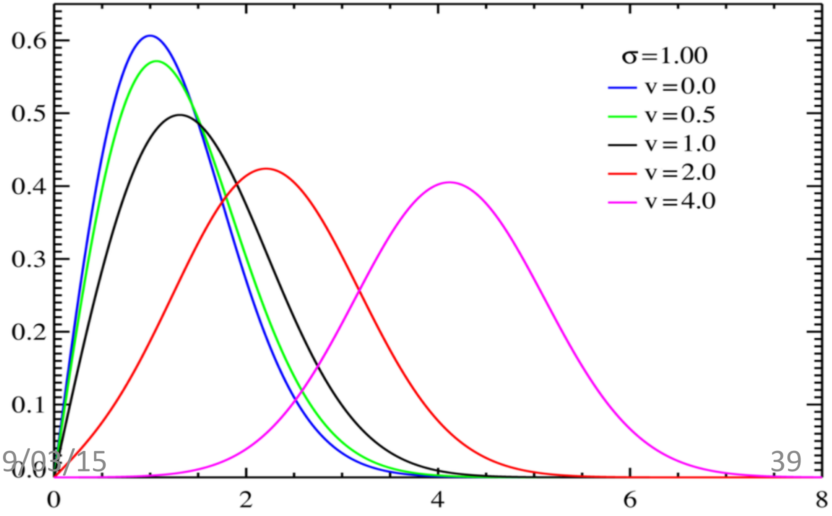
$$Y(t) \sim \mathcal{N}(\upsilon_2, \sigma^2)$$

$$f_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+\upsilon^2}{2\sigma^2}} I_0\left(\frac{r\upsilon}{\sigma^2}\right)$$

$$\upsilon = \sqrt{\upsilon_1^2 + \upsilon_2^2}$$

$I_{0:}$ Zeroth order modified Bessel function

$$K = \upsilon^2/2\sigma^2$$



Small-scale Fading Models (2)

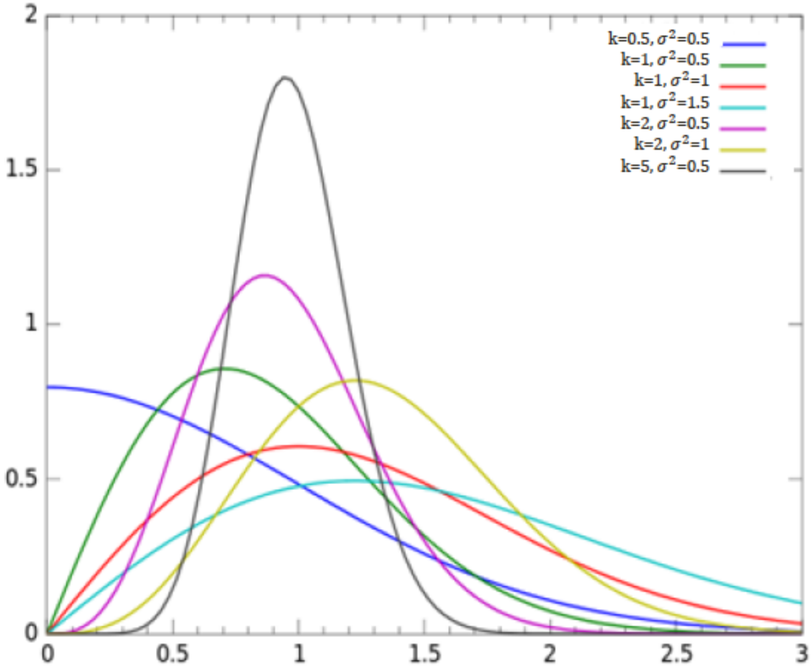
- Nakagami Distribution

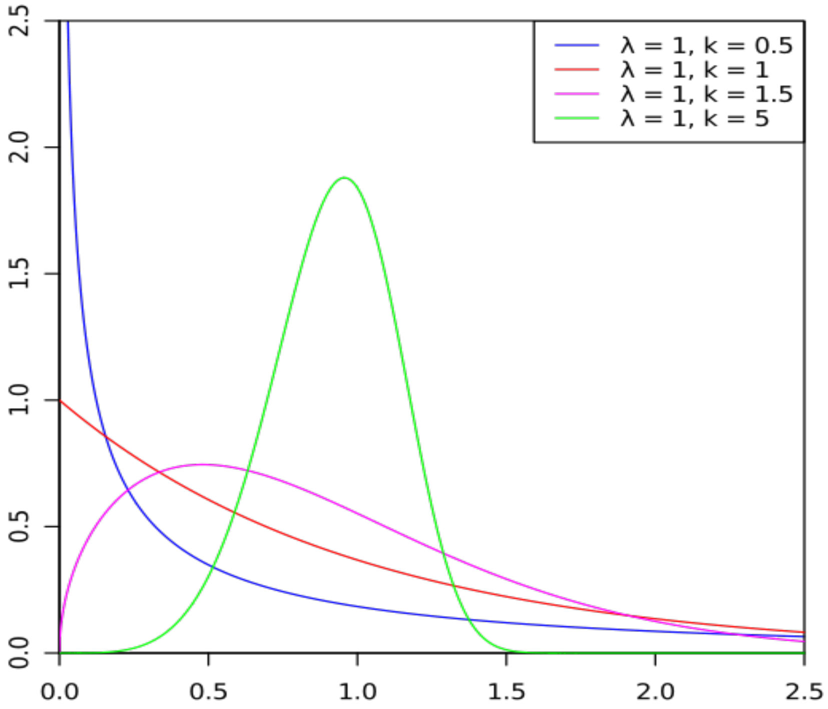
$$f_R(r) = \frac{2}{\Gamma(k)}\left(\frac{k}{2\sigma^2}\right)^k r^{2k-1} e^{-\frac{kr^2}{2\tau^2}}$$

k=1 Nakagami=Rayleigh

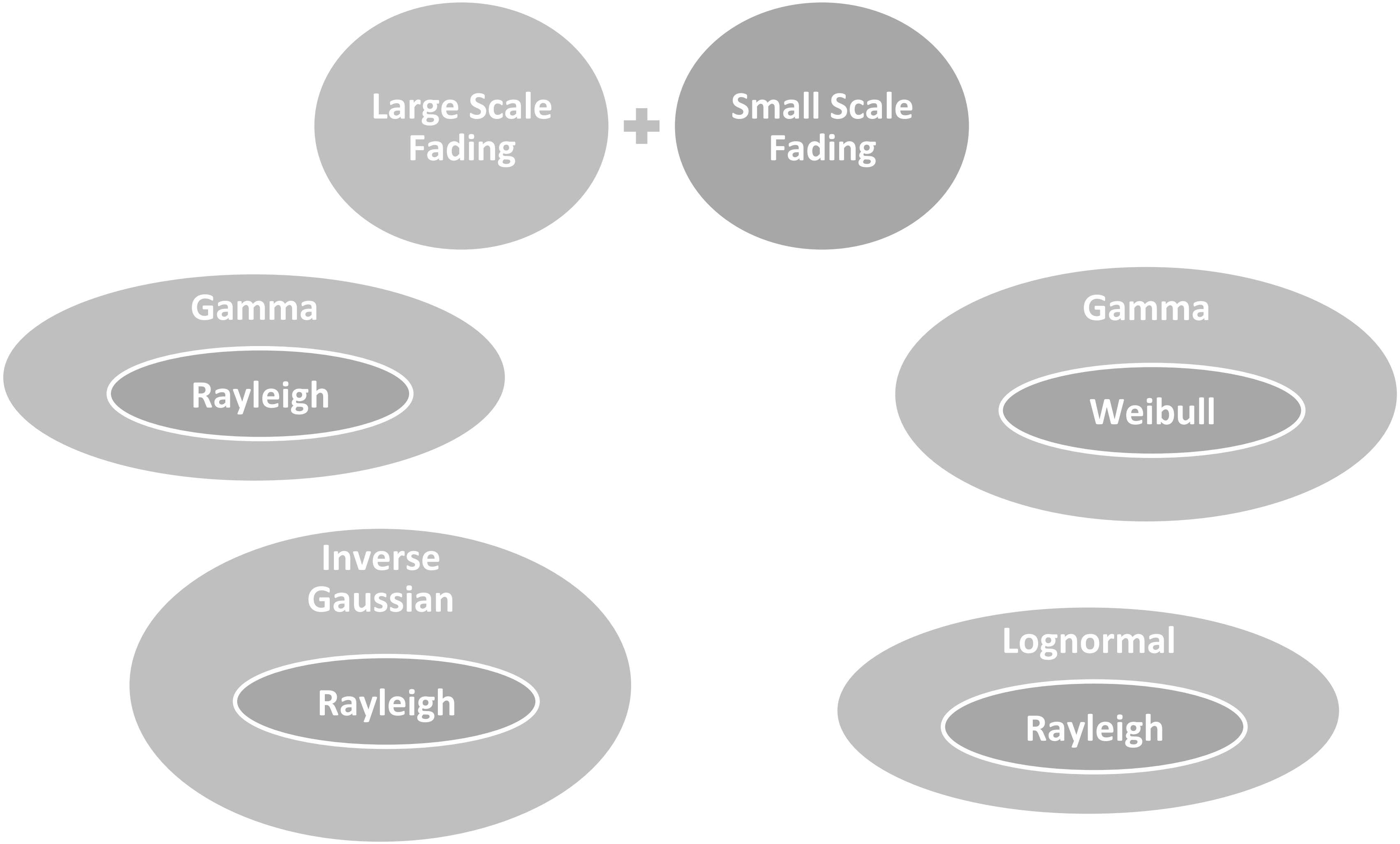
- Weibull Distribution

$$f_R(r) = \frac{kr^{k-1}}{2\sigma^2} e^{-\frac{r^k}{2\sigma^2}}$$





Composite Channel Models



Large Scale Fading + Small Scale Fading

Gamma

Rayleigh

Gamma

Weibull

Inverse Gaussian

Rayleigh

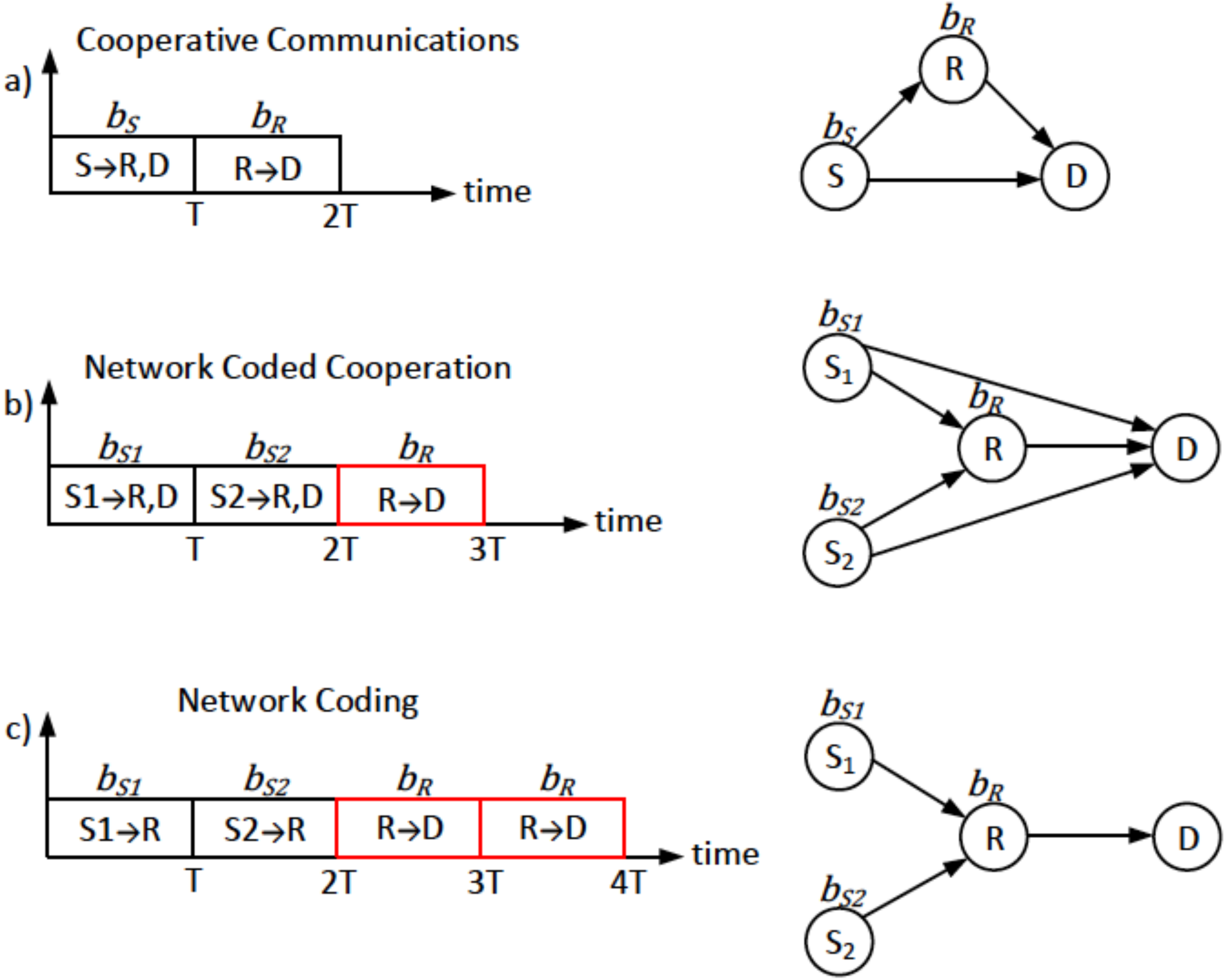
Lognormal

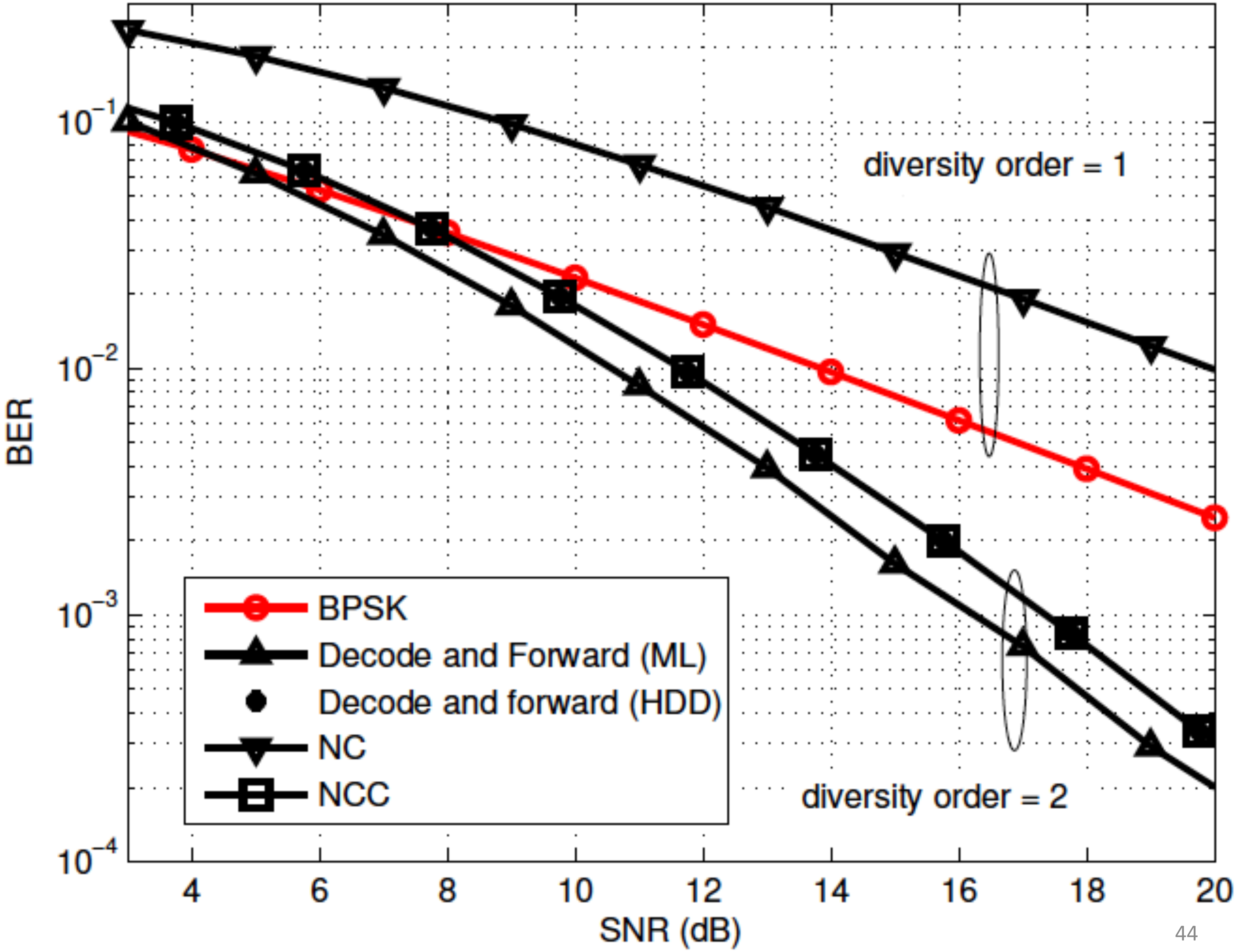
Rayleigh

Simulation Results

- Binary phase shift keying (BPSK) modulated transmission
- Rayleigh Fading + AWGN
- Two source nodes and a relay node
- Network coding @ relay node $\boxed{b_r = \alpha_1 \hat{b}_1 \oplus \alpha_2 \hat{b}_2}$
- (almost) Maximum likelihood detection at destination

$$\arg \max_{b_{s_1}, b_{s_2}} \{\ln(Pr(\hat{b}_{s_1} \mid b_{s_1})) + \ln(Pr(\hat{b}_{s_2} \mid b_{s_2}) + \ln(Pr(\hat{b}_r \mid b_{s_1}, b_{s_2})\}$$


a)
Cooperative Communications
b_S
b_R
S→R,D
R→D
T
2T
time
b_R
R
b_S
S
D
b)
Network Coded Cooperation
b_{S1}
b_{S2}
b_R
S1→R,D
S2→R,D
R→D
T
2T
3T
time
b_{S1}
S_1
b_R
R
D
b_{S2}
S_2
c)
Network Coding
b_{S1}
b_{S2}
b_R
b_R
S1→R
S2→R
R→D
R→D
T
2T
3T
4T
time
b_{S1}
S_1
b_R
R
D
b_{S2}
S_2


BER
SNR (dB)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
4
6
8
10
12
14
16
18
20
diversity order = 1
diversity order = 2
BPSK
Decode and Forward (ML)
Decode and forward (HDD)
NC
NCC